Declaration.

All of the papers and material presented are as a result of my own independent work.

William Ward 08/12/16.

Application of commercial, off the shelf (COTS) equipment to meteor astronomy.

ABSTRACT.

The explanatory essay discusses the rationale, methods and observational results using modern commercial, off the shelf (COTS) equipment in meteor astronomy. Much of the work is directed at developing spectroscopic observations and combining multi station observations to provide both orbital and compositional information about meteoroids. Papers are presented illustrating examples of the observations made and the significance of the results is discussed. COTS equipment is used primarily due to the reduced unit cost of such items. The cost of a typical system as used in this work, is in the region of £1000 for the camera, lens and grating (at time of writing).

Application of commercial, off the shelf (COTS) equipment to meteor astronomy.

Thesis Summary.

The work describes the results and advances in what is a developing field of observational meteor astronomy, survey video meteor spectroscopy. The combination of orbital determinations from multiple station observation and spectroscopic observations is a very powerful observational tool which is capable of giving an insight into the Earths' meteoroid environment that has hitherto been impossible to achieve.

Meteor astronomy is a difficult research field due to the random nature of the phenomena. Even during times of enhanced meteor activity, such as during known meteor showers, there is no guarantee of a successful observation. As well as unknown spatial appearance the short temporal duration of meteors compounds the difficulties further.

With technological advances and cost base reductions relatively low cost high sensitivity video cameras, used mainly for CCTV security applications, can now be applied to the problems of meteor observation. The observations presented show that using commercial, off the shelf (COTS) components it is possible to undertake observations of considerable significance. The work presented here illustrates how the existing limitations have now been overcome using this approach.

The results obtained represent a paradigm shift in meteor studies. The equipment described is now being employed by meteor scientists and amateur astronomers the world over.

Historically, it was with the development of suitable photographic processes and related optical equipment that a quantitative approach to meteor astronomy could be made. However the photographic process has extremely low quantum efficiency. Further development in the field relied on extremely specialist optical equipment. An example of such equipment is the large aperture, wide field system known as Super Schmidt cameras. The development of emulsion processes continued

until the 1990's but has now been superseded by electronic sensors such as CCD and CMOS technologies.

The principal approach to modern meteor astronomy is to employ as many of the low light cameras as is possible/practical in a continuous watch or “survey” mode. The video outputs being fed to a PC via a suitable frame grabber for capture and analysis. Using the appropriate motion detection software any event above a particular threshold will trigger the video stream to be recorded. By continually recording the video feed in time shift operation, several seconds before the trigger event can also be retrieved thus recording the whole meteor.

To complement the statistical and orbit information obtained by normal video methods the addition of a transmission grating to the optical path allows spectra to be recorded. Whilst simple to implement meteor spectroscopy has been generally considered a difficult task due to the low probability of success. As well as the observational difficulties mentioned, the addition of a dispersing element reduces the magnitude of meteors that can be detected. With the known distribution of meteor flux any reduction in the detection magnitude is a considerable penalty since there are substantially fewer bright meteors than faint. The main body of work shows that despite these difficulties the same consumer devices fitted with appropriate optics can be employed to the effect of greatly increasing the number of spectra captured. The lower cost of COTS equipment and associated improvements in efficiency have led to the new field of survey video meteor spectroscopy emerging. The general methods of image handling, reduction and results are discussed in the papers presented. The application of compact low light level CCTV cameras has revolutionised meteor astronomy.

Prior to the use of such cameras and methods, meteor spectroscopy was limited in scope to specific shower events, to improve the chances of success, and occasional fireball captures. This is no longer the case. Now, with regard to meteor showers, increasing the number of available spectra further allows for greater analysis of parent body sources and investigating short temporal duration phenomena. Also, working with multiple low cost cameras in a continuous watch mode offers access to the much larger sporadic meteor flux. Since the sources of meteoroid particles are taken to be either cometary or asteroidal in origin, video meteor spectroscopy offers the ability to potentially examine spectra of relatively primitive solar system material. This material has never undergone the processes of planetary formation and so represents the building blocks of the solar system.

The papers presented show the observational results gathered through survey video meteor spectroscopy and multi station observations.

Application of commercial, off the shelf (COTS) equipment to meteor astronomy.

Explanatory Essay for the Degree of Doctor of Philosophy by Published Work.

William Ward.

8/12/16

Application of commercial off the shelf (COTS) equipment to meteor astronomy.

Abstract.

This explanatory essay discusses the rationale, methods and observational results using modern commercial, off the shelf (COTS) equipment in meteor astronomy. Much of the work is directed at developing spectroscopic observations and combining multi station observations to provide both orbital and compositional information about meteoroids. Papers are presented illustrating examples of the observations made and the significance of the results is discussed. COTS equipment is used primarily due to the reduced unit cost of such items. The cost of a typical system as used in this work, is in the region of £1000 for the camera, lens and grating (at time of writing).

Rationale.

Scientific meteor observing is a unique challenge. Historically, due to the random occurrence on the sky, observing programs have tended to concentrate on major meteor showers when the chance of success was highest. These observing campaigns utilised specialist, high cost CCD cameras/optics and even aircraft (Jenniskens 2000). Despite the success of these campaigns the expense of such operations meant regular ongoing observations of this type are generally not carried out by many academic institutions.

Using COTS equipment has changed the position of regular ongoing observations and has had a very significant impact on the field of meteor astronomy.

Firstly, it has allowed the field to be opened up to a very much larger community of both professional academic and amateur astronomer's resulting in a large increase in observations. In the

UK there are significant amateur groups such as NEMETODE (http://www.nemetode.org) which has over 20 contributors operating over 50 cameras.

Secondly, the reduced unit costs now mean that large multi camera systems have been installed by major astronomical institutions. These include NASA/SETI Institute (http://cams.seti.org/), CAHA Observatory, southern Spain, (http://www.caha.es/press-release/blog.html) Spain and the Instituto Astrofisica de Canarias (IAC) on the Canary Islands (http://www.imo.net/new-operational-spectral-meteor-cameras-on-the-canary-islands/). These larger systems, up to 40 cameras at a single location, give far greater sky coverage and observing efficiency.

The research presented here, initially started in November 2008, demonstrate that due to advances in technology new results can now be obtained in an ongoing "survey" basis as opposed to short term targeted campaigns. The results reveal newly observed phenomena and represent a paradigm shift in meteor observing.

1: Introduction.

Contemporary meteor astronomy has long been the preserve of the amateur astronomer. Due to the random appearance of meteors on the night sky it takes determination and enthusiasm to conduct productive observations. However, using nothing more than patience and the naked eye a considerable body of data has been built up over time. The interested reader can access the International Meteor Organisation Visual Meteor Database (VMDB) which contains nearly 4,000,000 standardised observations at http://www.imo.net/members/imo_vmdb

This has been the foundation of much further professional research.

Following World War Two, and perhaps because of it, there were significant advances in photography and development of large format large aperture optics. In particular a series of specialised meteor cameras based on the Schmidt optical configuration were built in the USA and a smaller version was developed by UK meteor scientists. These cameras were known as "Super

Schmidt” cameras. Such instruments allowed observations to be made at magnitudes considerably fainter than previously achievable. Also, and perhaps more importantly an objective and permanent record of the meteors observed could now be made (Whipple 1955, Jacchia and Whipple 1956, McKinley 1961).

This technology was, however, ultimately limited due to the extremely low quantum efficiency of the photographic emulsions. Using film, meteors had to be in the minus magnitude range to be even captured. Consequently, the magnitude of a meteor required to produce a measurable spectrum was significantly brighter (Hawkins 1964). This was the situation until the 1990’s when the emergence of commercially available electronic solid state detectors superseded film emulsions. Initially relatively insensitive detectors were improved by the addition of microchannel plate image intensifiers. However such detectors and associated optics tended to be of relatively high cost (McClean 1989, McClean 1997).

It was not until the early 2000’s thanks to the availability of low cost, extremely sensitive video cameras and computer controlled video processing that meteor astronomy began to make significant progress again (Murad and Williams 2002). The entire field of meteor astronomy is being revolutionised by the successful development of video meteor spectroscopy using compact low light level CCTV cameras. The camera technology has been primarily driven by security and machine vision applications. However the performance of this technology is such that these cameras have become the premier tool in observational meteor astronomy for both the amateur and now the professional too.

This essay describes the equipment and methods used in the application of such “commercial off the shelf” equipment to meteor astronomy with particular attention to the utility of such cameras in the area of video meteor spectroscopy.

2: Equipment.

In all of the papers presented the cameras used have been made by the Watec Company of Japan. Sensitivities quoted by the manufacturer are, with reference to EIA standards, in the milli-lux range. In astronomical applications these specifications are of little direct value. With meteor astronomy in particular, it is the actual ability to detect a rapidly moving phenomenon at a sufficient signal to noise ratio which is of importance. Coupled with suitable optics the Watec cameras provide excellent performance.

The Watec cameras are based around Sony ® "ExView" CMOS sensors. The cameras produce a 1 volt peak to peak video signal in the PAL standard (the normal for the UK). The sensors operate in an interlaced mode. This means two 1/50 second exposure fields on alternate rows of pixels are read out and combined to produce the 25 frames per second video rate.

Two models of cameras were used in all of the work here, the Watec 902 H2 Ultimate and Watec 910 HX/RC. Both cameras have "½ inch" sensors with 752x582 effective pixels. The pixel size is 8.6 microns by 8.3 microns. Full camera specifications are given on the manufacturer's website http://www.watec.com/English/e_index.html

The video output is taken from the camera and fed to the motion sensing and recording software via an 8 bit (256 levels) video frame grabber. The frame grabbers utilised are inexpensive Compro branded PCI cards (~£30). The motion detection software package used is UFO Capture by SonotaCo, Japan running under Windows XP on Dell 780 dual core processor personal computers. Despite the rather science fiction type name, UFO Capture is an extremely powerful suite of software designed specifically for the capture and analysis of meteor phenomena.

The video stream is recorded by a time shifted motion capture method. Once a threshold of pixel value has been exceeded for a particular length of time value or pixel area set by the observer, the event is recorded along with the preceding seconds allowing the whole meteor to be captured. The system then logs the video and co-adds the individual video frames into a variety of composite still images for further analysis.

In low light level conditions to achieve the best performance lenses with large physical apertures are needed. Lens selection requires some compromises to be made. Due to the random nature of meteors on the sky it is desirable to image as much of the sky as possible. However due to the small image scale produced by wide field lenses and the limited pixel size, wide field lenses do not generally produce good results particularly in regard to spectroscopy. At the other extreme, long focal length, narrow field of view lenses offer a much better image scale but they also suffer a much reduced view of the sky. Since first conducting spectroscopic observations in late 2008 and through several years of further observation and experimentation it has been found that lenses of the standard 12mm focal length and focal ratios of f1.2 or f0.8 produce good results. The 12mm focal length produces an effective field of view of 31 x 23 degrees on the 6.4mm by 4.8mm sensor of the Watec cameras. Figures 1 and 2 show the general configuration of a typical camera system as used by the author.

To capture a spectrum requires the addition of a suitable dispersing element to the optical path. Traditional spectroscopy generally uses a slit to produce images of the lines however by their nature meteors appear as streaks of light against a dark background. Therefore they behave effectively as their own slit. The transmission grating is mounted immediately in front of the lens. It is held in place by the lens hood screwed into a suitably sized adapter ring attached to the lens. These mounting rings are available from any photographic store. A complete spectrum is built up by the video recording system as the meteor moves across the sky. The heating element consists of a 1.5 m length of NiCr wire inside a comparable length of heat shrink tubing. This is wound into the lens hood and taped into position. With the NiCr wire available (approx. 20 ohms/meter) and a nominal 12v DC power supply the power dissipated is around 7 watts. The heater is an essential component as it is needed to prevent dew condensing on the grating. The heater must be kept clear of all optical surfaces to prevent the risk of thermal damage.

After a period of observing with this system through the winter of 2008 it was noted that the addition of the grating had turned a simple camera system into a powerful observational tool.

Another key aspect of this type of system is automation. The camera operation, in the observational sense, can be configured to work without human intervention. Through the deployment of multiple cameras and the capability of conducting observations without human fatigue the efficiency of data collection is greatly increased.

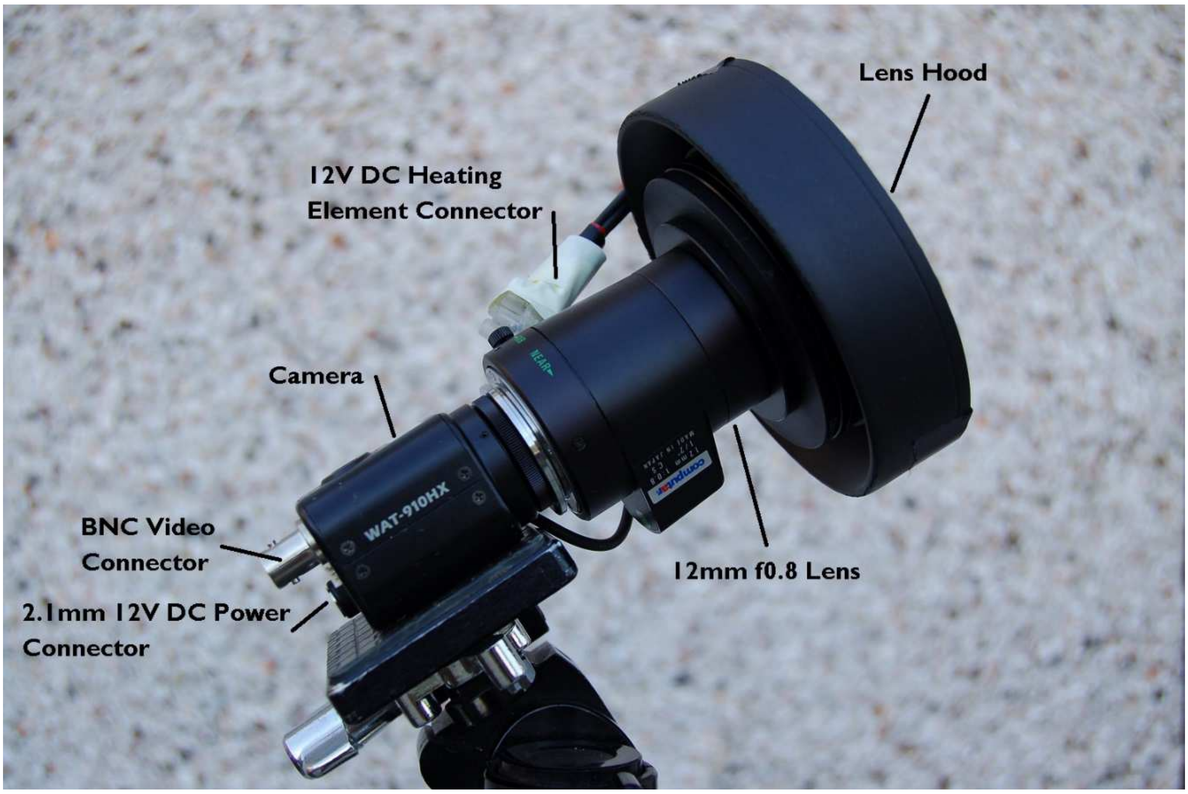


Figure 1. General camera configuration.

Figure 2. Grating mounting and heating element arrangement.

3. Analysis.

After capture the composite video images can be exported to the sub programs UFO Analyser and UFO Orbit. Then, in collaboration with other observing stations, they can be used to produce orbits for the captured meteors. With spectroscopic systems it is only possible to use the zero order image, if captured, for orbit determination. However in most cases the zero order image is not captured. When working with other observing stations it is possible to identify simultaneous meteors through accurate event timings or by the use of additional video cameras suitably positioned with respect to the spectroscopic camera to capture the “ordinary light” image of the meteor.

In spectroscopic applications a significant limitation of the transmission grating is that dispersion is along one axis only. As the motion of any given meteor is in a random direction on the sky it requires an element of good fortune to record a spectrum that is well dispersed. That is, having the meteor travel in such a way that it is not significantly degraded by passing at too shallow an angle with respect to the dispersion axis. Observationally this is not an ideal situation. However due to cost reductions the use of COTS equipment allows multiple cameras to be in operation thus increasing the chances of a successful capture. The deployment of such systems has been expanded greatly in some cases now that the utility of the equipment and methods have been proven. Systems such as those deployed by NASA/SETI Institute have up to 40 cameras per installation for complete sky coverage and at multiple locations.

Spectroscopic analysis requires additional image processing steps to reach a finished spectrum. As noted the orientation of the meteor on the sky is random. Thus the orientation of the meteor flight can be in any direction across the field of view. Therefore the spectrum is frequently not aligned with the actual dispersion axis of the grating.

The meteor image must be firstly rotated such that the spectrum dispersion runs horizontally across the image, then the angle of tilt must be corrected so that the spectrum lines are vertical. Figures 3, 4 and 5 show representative images of the re-orientation required.

Figure 3. A typical meteor capture.

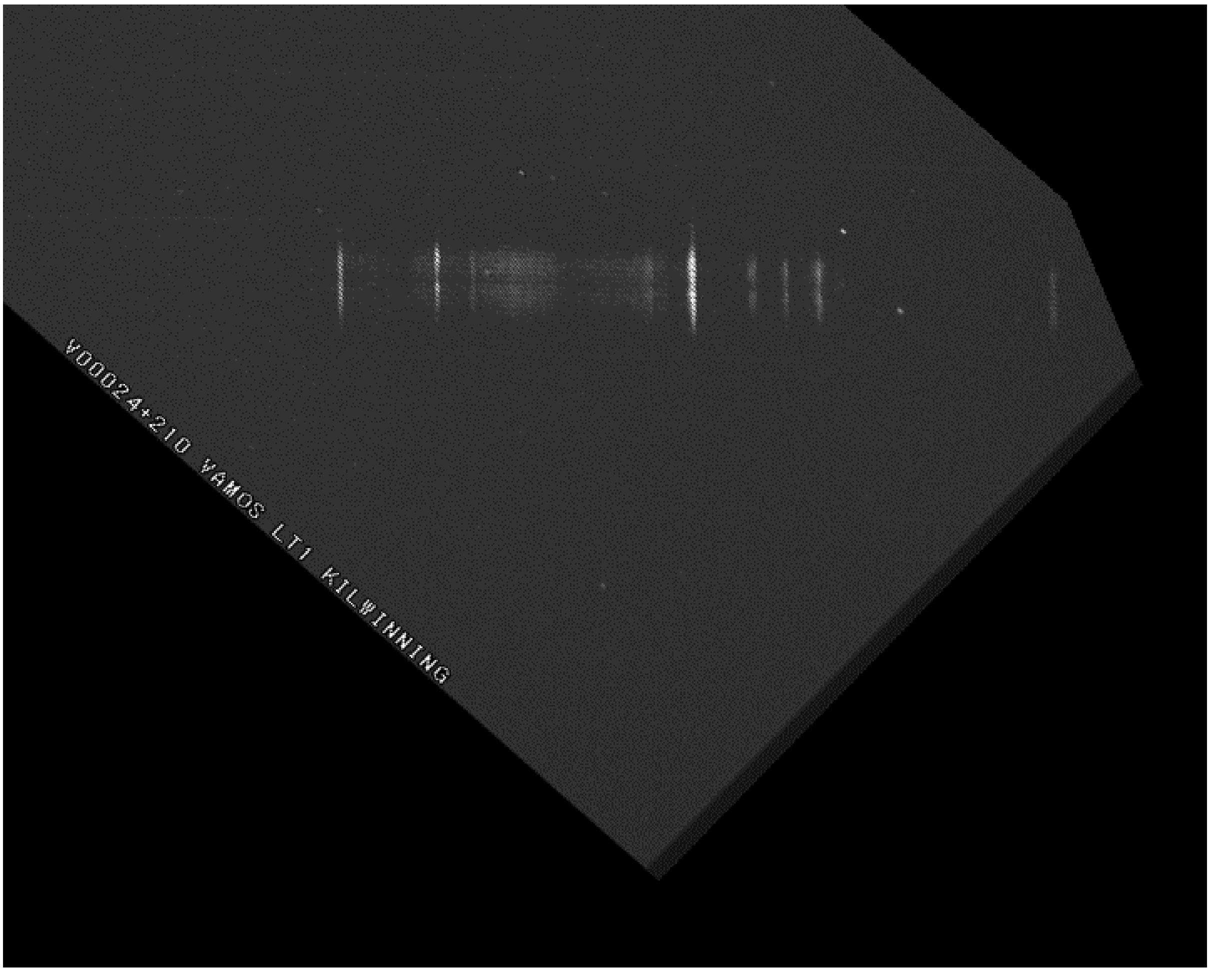


Figure 4. Meteor re-orientated, correcting for rotation and slant using IRIS.

Figure 5. Cropped image.

The spectrum is oriented such that the wavelength runs from blue to red, left to right across the image. This configuration is dictated by the spectrum processing package Visual Spec. This software can import images in several formats providing the original spectrum has been suitably pre-processed in this way. In essence the spectrum is produced by performing a pixel value summation up the columns along the width of the spectrum. The spectrum profiles are saved as two column text files. One being wavelength as determined by the calibration and the other the pixel value. The pixel values are auto-scaled by the software during plotting but can be arbitrarily scaled manually. Using this file graphical spectrum plots can be produced with any third party plotting software such as GNUplot.

Additional issues that may need to be addressed are the correction of optical aberrations and any uneven-ness in frame illumination. Transmission gratings produce an almost linear dispersion with respect to wavelength however this is superimposed on aberrations present in the lens optics. Depending on the location within the field of view this can (sometimes) result in a curved spectrum due to what is known as barrel distortion. Specialist astronomical image processing packages such as IRIS can be used to eliminate this. During the process of line identification, corrections to the uneven dispersion caused by the aberrations can be done on an ad hoc basis over short wavelength intervals. It should be noted this method is limited to low/moderate resolution spectra. In practice it has proved satisfactory at the resolution achievable with the equipment as described

The images can then be flat fielded if required. This is the term used for the division of the raw image by one taken of a uniform source of illumination. This corrects for uneven illumination at the focal plane due to vignetting by the lens design and/or a brightness gradient in the sky. A short video of a white screen is taken and a median stack of a group of individual video frames was produced with IRIS. Due to the relatively narrow field of view and generally good field illumination produced by the 12mm lenses used this was not generally not done in normal practice though.

Line identification and wavelength calibration is performed by comparison to both existing spectra in the meteor literature in the first instance then refined by comparing the (unknown) measured lines to those of reference libraries of atomic emissions. Visual Spec, being written for astronomical use has an inbuilt library which is very useful in most cases. Further identifications can be made using larger libraries such as the ones available at the National Institute of Science and Technology (NIST) (http://www.nist.gov).

Once the spectrum is wavelength calibrated it can be corrected for instrument sensitivity. The silicon detectors used in the Watec cameras have high near infrared wavelength (>750nm) sensitivity whilst having relatively poor blue wavelength sensitivity (<400nm). Many simple examinations and inferences can be drawn from spectra without instrument correction but it is necessary when comparing different data sets from different camera systems to ensure correct interpretation.

Instrument correction is achieved by dividing the spectrum with a radiometrically corrected spectrum of a known source. The star Vega, class A0V, is an established standard and has a spectrum that is well defined. Class A stars have relatively few features apart from prominent lines from hydrogen and are so convenient to use. The strong hydrogen lines in the spectrum are first removed to give a smooth continuum. This procedure is done within Visual Spec. The continuum is then used to divide through the meteor spectrum to produce the final instrument corrected version of the spectrum. Using the example of figure 5 the processed spectra are shown in figures 6 and 7.

This particular example (figure 5) also shows a problem that occurs with such wide field spectrum imaging. Occasionally a background star will be captured within the spectrum image. This will be included in the summation done with Visual Spec and will appear as a false feature in the spectrum. However, again the software has various utilities for removing such artefacts. In this case the star was deliberately left in to illustrate the effect.

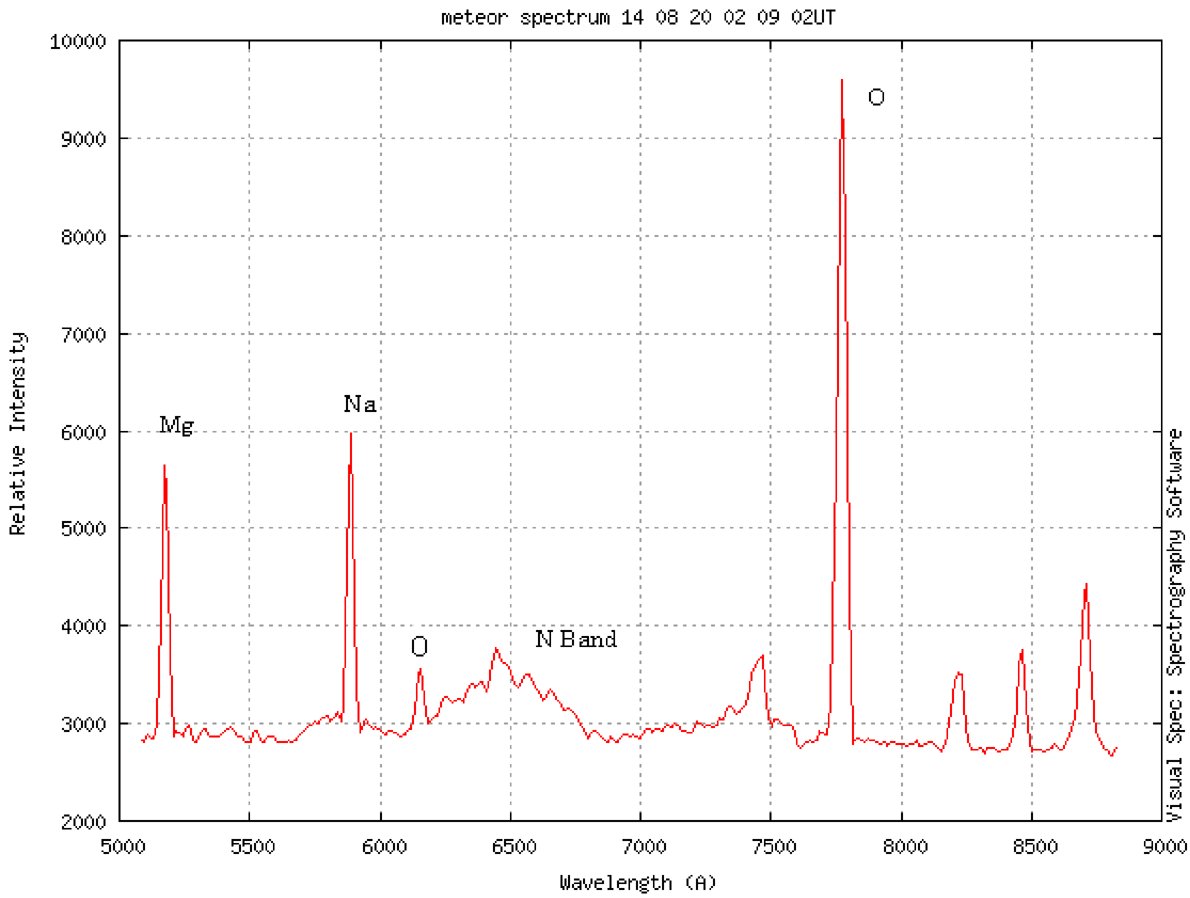


Figure 6. Non instrument corrected example spectrum from figure 5. Some major lines are identified.

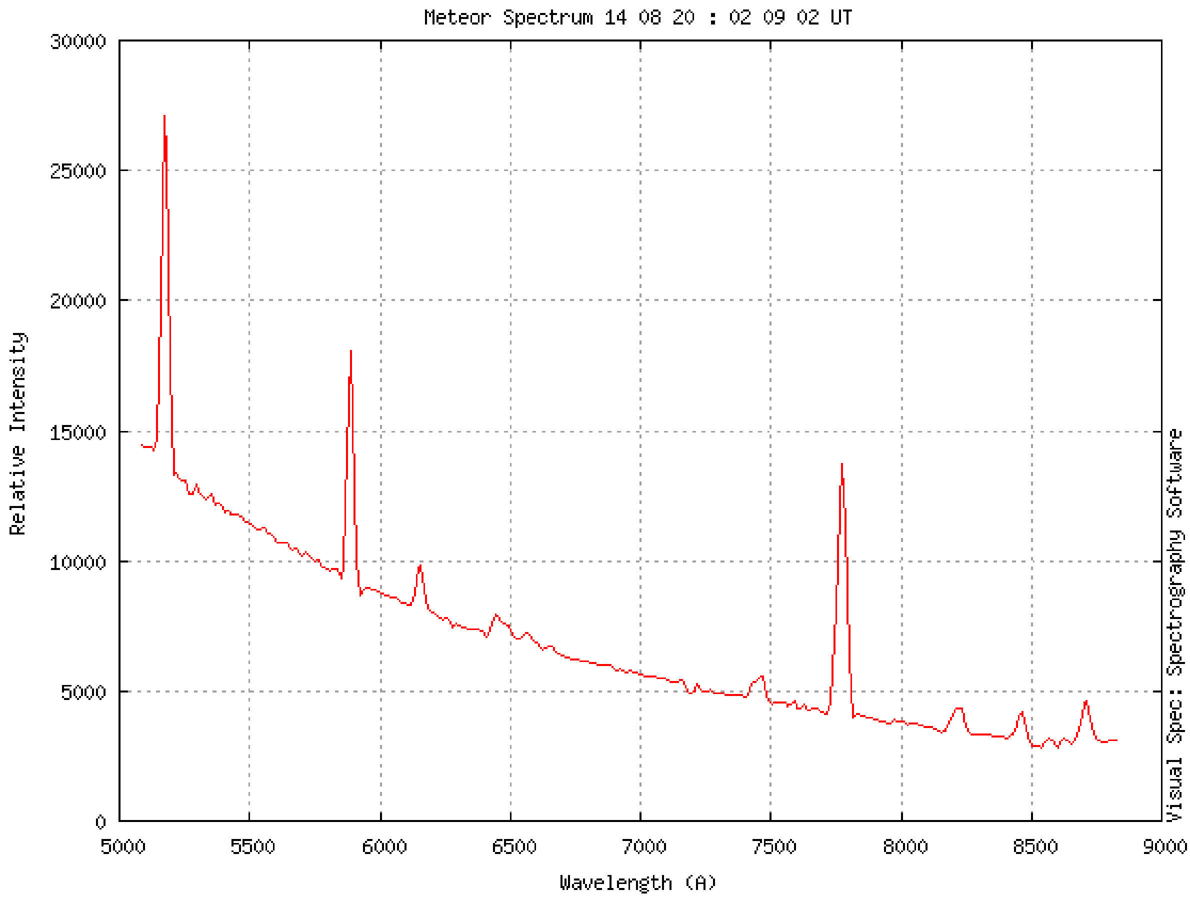


Figure 7. Instrument corrected example spectrum of figure 5.

4. Published papers.

4.1. Meteor Streams. Meteor spectroscopy during the 2015 Quadrantids. (1)

With the ability to deploy several cameras at any one location dramatically increases the chance of capturing a meteor bright enough to produce a spectrum with good signal to noise ratio. Rather than one or two per year it may be one or two per night and more on nights of high activity.

The large increase in efficiency means that during meteor showers it is possible to obtain a sufficient number of spectra to directly examine the compositional properties of the multiple members of the stream. This is of importance as a greater number of spectra with similar properties gives confidence in the particular compositional characteristics observed. If a baseline characteristic can be established with high confidence it means that further spectra may reveal variations between particles shed from the parent body during different orbits offering an insight as to the parent body evolution. Observations of this type have only now become practical due to the large number of spectroscopic cameras in operation. The paper demonstrates this by showing multiple, near identical spectra obtained from meteors in the stream. It is interesting to compare these results to the ones obtained by J. M. Madiedo (Madiedo 2016) using similar equipment.

4.2. The sporadic population. Spectro-orbital observation of a sporadic meteor. (2)

Although the popular concept is that most meteors occur in showers this is in fact incorrect. The Earth encounters a vastly greater number of meteors classified as “sporadics”. Sporadic meteors are meteors that have no clearly defined association to any known shower or parent body. These represent by far the largest population of meteoric material scattered throughout the solar system. (Weigert 2009)

Using the same Watec cameras but without any gratings mounted allows normal video recordings of meteors to be made. With large numbers of meteors being captured regularly combined with the ever growing number of cameras at many locations leads to the situation where a significant fraction of meteors are now captured by multiple stations. With multiple station captures a unique orbital solution can be derived from astrometric measurements made using the composite video images.

The various sub-components of the UFO Capture software, UFO Analyser and UFO Orbit are used to determine the orbital elements. UFO Capture produces an .xml file of positions and time within the image frame which is in turn used by UFO analyser to determine astrometric positions. The output file from UFO Analyser a .csv file is then utilised by UFO Orbit in combination with observations from various stations to produce a set of orbital elements and various graphical representations. Full details are given the users manuals available from http://sonotaco.com/e_index.html

The addition of spectroscopy to regular video meteor observing means that a study can now be made of the compositional characteristics of the sporadic population in general. Until recently this was almost impossible, relying on occasional captures of "fireballs" on dedicated wide field photographic camera systems (Borovicka 1993, Ridley 1994). These systems were set up specifically to look for very bright events that may lead to the recovery of a meteorite. The issue with this approach is that such extremely bright events tend to be from more solid material taken to be of asteroidal origin. Cometary material is much more friable and thus highly unlikely to survive passage through the atmosphere.

Hence video spectroscopic observations can reveal information about meteors from both cometary and asteroidal sources. With the exception of recent spacecraft observation, the European Space Agency Rosetta mission for example, no other technique offers this possibility. This paper discusses the use of combining the techniques of spectroscopy and orbit determination. The result obtained was the first ever observation, by two stations based in the United Kingdom, of the same meteor where a spectrum was also recorded. The paper illustrates the relative ease with which this kind of observing programme can now be carried out.

4.3. Dynamical processes. Analysis of a Perseid fireball spectrum. (3)

The meteor process itself is rapid and violent. The particle travelling independently in its own orbit will be at its thermal equilibrium with respect to the incoming solar radiation. Upon entering the Earth's atmosphere the temperature rises extremely quickly through frictional collisions to several thousand degrees kelvin and suffers an equally extreme deceleration imposing large crushing forces on the particle (Opik 1958). It is this combination of physical effects that generates the disintegration and excitation of the mineral elements leading to the emission spectrum produced. Recent contemporary spectroscopy was conducted using integrating cameras such as CCD based devices. These offer high wavelength resolution but contain little temporal information. Photometric plots can be made along spectrum lines but at very short time intervals rapidly evolving phenomena are generally lost.

Video techniques offer a possibility to recover this information and examine in detail the evolution of individual spectrum lines limited only by the video frame rate employed. Each video frame is in essence a very short "snap shot" in the evolution of the spectrum. The video frame rate operates as an effective "chopping shutter" giving a time reference to each individual video frame. This allows time resolved observations of the meteor to be made.

In this paper a very bright Perseid fireball is discussed. By utilising the time resolved nature of the individual video frames the meteor terminal flare was seen to exhibit changes in the spectrum as the flare faded and the surviving fragment separated. Contrast this to examining the video composite image in itself where none of the effects can be seen. This was the first time that such an observation of the changes within a terminal flare from a Perseid meteor had been made from the UK using video techniques.

4.4 Spectroscopic and orbit determination. Video meteor spectroscopic and orbit determination observations. (4)

The most powerful application of survey video meteor spectroscopy is expressed when it is combined with other multi station observations. Yielding a compositional analysis and an orbit represents the most complete characterisation of the meteor. The paper presents results obtained over the period from April 2015 until April 2016 and illustrates the wide range of properties displayed by meteors encountered by the Earth. The utility of the equipment and methods can be seen in the broad range of results obtained. It expands on the initial results given in paper 2 with a greater number of samples showing how this data can only build up over time. This initial collection of results, gathered in collaboration with many amateur astronomers, represents the first such efforts with this technique in UK astronomy.

Every meteor capture is unique in terms of its orientation within the frame, linear dimension with the frame, magnitude, duration and sky conditions. Although all of the spectroscopic systems used the same model of camera a common image reduction process to fully correct the image is not possible. Each and every capture requires a unique solution. For expediency, given time and other practical operational limitations, only basic image geometry corrections were done before importing them into Visual Spec. No flat fielding or noise subtractions were carried out in the spectra presented. However to make some qualitative comparison possible the spectra were normalised over a wavelength range where there were few if any lines present.

Spectra can be analysed to determine the ratios of the most prominent lines normally seen. These being sodium (Na), magnesium (Mg) and iron (Fe). These elements can be used to construct ternary diagrams from which mineralogical inferences can be drawn. This can give an insight to the age and evolution of the meteoroid (Borovicka 2005, Kasauga 2006). This is an area for future development.

4.5 Additional application of COTS equipment. High altitude wind traced by a persistent train from a Geminid fireball. (5)

Although the study of meteors is generally considered a field of astronomy it should be remembered that the actual meteor is a phenomenon that occurs in the Earth's upper atmosphere. Under suitable conditions it is possible to use the meteor as tool to probe the atmosphere rather than examine the meteor itself. Meteors "burn up" at approximately 90km in the region of the atmosphere known as the mesosphere. At this altitude the pressure is only one ten thousandth of that at sea level. However the mesosphere is still subject to the influence of solar heating and the transportation of energy from lower in the atmosphere.

Whilst investigating the use of consumer grade digital SLR cameras as an accessory to video observing several extremely bright meteors from the Geminid meteor shower were captured whilst conducting tests at the Instituto Astrofisica de Canarias (IAC) on Tenerife in December 2012. These tests were done to try and achieve better astrometry for use in conjunction with meteor spectra images captured by video systems. The camera and lens used were a Canon 1000D with a Sigma 30mm f1.4 lens. A piece of plastic grating material with 500 lines per mm (lpm) was mounted in an empty filter holder and attached to the lens. The plastic grating material was obtained from Edmund Optics UK. This is a plastic holographic film grating, a type of grating in which a sinusoidal "blaze" pattern is generated on the surface by exposing the grating (covered with photoresist) to an interference pattern. The sinusoidal variations in the interference pattern lead to the groove profile for the holographic element. Edmund Optics part number: #54-509.

One in particular was exceptionally bright and also happened to be observed visually. Inspection of the images revealed it had left what is known as a persistent train. This is made up of surviving "smoke" from the meteor and if the event is sufficiently energetic it is self luminous through interaction with atmospheric molecules. The persistent train was seen in 22 frames. The movement indicated it was being blown by the mesospheric winds. The train lasted eleven minutes before finally dissipating. By simple geometric calculations it was determined that the mesospheric wind was travelling at 137m/s (approximately 499kph). This is amongst the fastest wind speeds ever measured on Earth. For comparison the fastest confirmed wind speed gust in the troposphere is 113.3m/s (Courtney 2012).

The results were published in the paper “High altitude wind traced by a persistent train from a Geminid fireball” and also presented at the International Meteor conference in Poznan, Poland 2013.

5. Commissioned Work.

As video meteor spectroscopy is a new and developing field of astronomy the author was invited by the Editor of the popular astronomy magazine, Astronomy Now, to write a feature on the developments of video spectroscopy techniques. The brief specified the article be aimed at a non-specialist audience but one having a basic understanding of the techniques of spectroscopy and what it can say about physical astronomical phenomena.

Spectroscopy is the key method for analysing astrophysical phenomena and in standard astronomical texts stellar spectra are often presented as being coloured bands with various absorption lines. These simulate the appearance of a spectrum as if produced by traditional laboratory spectroscopes. By re-mapping the meteor spectrum files using the appropriate utility in the Visual Spec spectroscopy software it is possible to assign the colour to the calibrated wavelength thus generating a representative synthetic colourised version of the spectrum. This in effect generates the colour band style spectrum. It was thought the target audience may be more familiar with this presentation rather than formally plotted spectrum graphs. This is the first time that meteor spectra will be presented in this way in the printed media.

Since meteor spectra are emission spectra they have the appearance of bright emission lines on a fainter continuum. With the near monochromatic nature of the emission lines the saturation of the spectrum colours produce an attractive and informative version of the spectrum. The brightly coloured lines can be easily associated with the common elements present in the spectra such as the yellow emission from sodium and so on.

This article was published Astronomy Now, October 2016, pages 100 – 103.

6. Conclusions and Future Work.

The work presented here represents the development of a new field of meteor astronomy, that of "video meteor spectroscopy". Rather than the use of highly specialised and generally expensive equipment of the past the application of consumer grade components has allowed the field to both open up to many more participants and to develop extremely rapidly.

The development of these techniques as a mainstream scientific method is illustrated by the increasing number of institutionally funded programmes. Utilising multi camera and multi station systems such organisations include the NASA Ames Research Institute/SETI Institute CAMS system (http://cams.seti.org/) and the Spanish and German Institute for Astrophysics (CAHA) at Calar Alto in southern Spain (http://www.caha.es/press-release/blog.html). Both of these institutions now operate spectroscopic systems based on the same components used in the papers presented here. In these systems there are as many as forty cameras arranged to image the entire sky in "normal light" and twenty spectroscopic systems. There are now many dozens of privately owned, amateur observing stations with a growing number conducting spectroscopic observations. Many of these stations work under the umbrella of the International Meteor Organisation (IMO). http://www.imo.net

The combination of standard video astronomical observing techniques combined with video meteor spectroscopic techniques is now allowing a completely new insight into the earth's meteoroid environment. Whether the source of meteoroid particles is either cometary or asteroidal the observational methods described allow direct examination of what may be relatively primitive solar system material. This is important to understanding the formation and evolution of the solar system by showing how material evolves and is dispersed over astronomical time (Nesrovny 2011). The ability to conduct spectroscopic observations at times out with major meteor showers is a significant step forward. This will allow examination of the compositional parameters of the large sporadic population to be determined and will potentially reveal unknown parent sources.

Through their low cost and ease of use the deployment of multiple cameras at many locations is providing large amounts of completely new data. Though inexpensive the new generation of low light level CCTV type camera when equipped with a suitable lens/grating combination has become the single most powerful astrophysical tool currently used in observational meteor astronomy.

Future work to fully correct images and characterise the various noise performance of the cameras and video capture devices should be made to allow quantitative analysis of the spectra. This will be become more important as the availability of data from many stations grows over time.

With the large increase in available data future work will involve the development of a comprehensive new meteor taxonomy. By analysing many spectra it should be possible to determine if there are related families of meteors. Also, as the number of observations increases comparative spectroscopy can be used to determine possible new associations between existing meteor sources and sporadic meteors. This a good example of study that is only possible using spectroscopy and cannot be done in any other way.

References and suggested further reading.

Borovicka J., 1993. Fireball Spectrum Analysis. Astronomy and Astrophysics. 279, 2, 627.

Borovicka J. et al, 2005. Survey of meteor spectra and orbits. Icarus 174, 1, 15.

Courtney J. et al, 2012. Documentation and verification of the world extreme wind gust speed record. Australian Meteorological and Oceanographic Journal. 62, 1-9.

Hawkins G.S. 1964. Meteors Comets and Meteorites. McGraw Hill.

Kasauga T. et al, 2006. Thermal desorption of sodium in meteoroids. Astronomy and Astrophysics. 434 L17-L20

Jacchia L.G. and Whipple F.L., 1956. The Harvard meteor programme. Vistas in Astronomy. Vol 2, 982-994

Jenniskens P. et al. 2000. Leonid Storm Research. Springer.

Madiedo J. M. et al, 2012. Observations of the Quadrantid meteor shower 2008 to 2012. Icarus. 275, 193 - 202.

McClean I. S., 1989. Electronic and Computer Aided Astronomy. Ellis Horwood.

McClean I. S., 1997. Electronic Imaging in Astronomy. Wiley Praxis.

McKinley D.W.R., 1961. Meteor Science and Engineering. McGraw Hill.

Murad E. and Williams I.P., 2002. Meteors in the Earth's Atmosphere. Cambridge University Press.

Nesrovny D. et al, 2011. Dynamical model of the Zodiacal cloud and sporadic meteors. Astrophysical Journal. 743, 129.

Opik E.J.,1958. Physics of Meteor Flight in the Atmosphere. Dover.

Ridley H.B., 1994. Spectrum of a Sporadic Fireball. JBAA. 104, 92.

Weigert P. et al, 2009. A dynamical model of the sporadic meteoroid complex. Icarus. 201, 295 – 310.

Whipple F.L., 1955. Meteors. Astronomical Society of the Pacific. 67, 367.

Acknowledgments.

The author would like to thank Prof Marc Sorel and Dr David Muir, School of Engineering, University of Glasgow for their help and ongoing support for this work.

The author would also like to thank Dr Tony Kelly for his encouragement and facilitating the submission of this work.

List of publications.

1. Ward. W. *Analysis of a Perseid fireball spectrum*. J.Br Astron.Assoc. 126:4, 207-209. 2016.
2. Ward. W. *Meteor spectroscopy during the 2015 Quadrantids*. WGN, JIMO. 43:4, 102-105. 2015.
3. Ward. W. *Spectro-orbital observation of a sporadic meteor*. WGN, JIMO. 43:4, 106-108. 2015.
4. Ward. W. *Video meteor spectroscopic and orbit determination observations.* J.Br Astron.Assoc. Accepted July 13, 2016.
5. Ward. W. *High altitude wind traced by a persistent train from a Geminid fireball*. WGN, JIMO. 41:5, 160-161. 2013.

Published commissioned work.

- Ward. W (Bill). Video meteor spectroscopy. Invited article by Astronomy Now magazine. 21/7/16. Published October 2016.

Conference proceedings.

1. Ward. W. *High altitude wind traced by a persistent train from a Geminid fireball*. IMC Proceedings, 21-25 August 2013, Poznan, Poland. Vol 1, pg 108. ISBN 978-2-87355-025-7.
2. Ward. W. *Video meteor spectroscopy*. IMC Proceedings, 27-30 August 2015, Mistelbach, Austria. Pg 115-116. ISBN 978-2-87355-029-5.

Work related award.

George Alcock Memorial Award 2015 by The Astronomer magazine (ISSN 0950-138X). This award was for work considered outstanding in the field of observational astronomy and for contributions/observation submissions to the magazine over the preceding several years.

Analysis of a Perseid fireball spectrum

Bill Ward

Analysis is presented of a Perseid fireball spectrum recorded by videography on the night of 2013 August 12/13. This is unusual in that two significantly different spectra were obtained in one of the video frames, which we interpret as being due to an afterglow following an end flare of the fireball and emission from the surviving fragment.

Introduction

Video meteor spectroscopy observations were made from Kilwinning, North Ayrshire, UK on the night of 2013 August 12/13 during the Perseid meteor shower peak. A bright fireball was captured of sufficient brightness and had a path such that the 1st, 2nd and part of the 3rd orders of spectrum were recorded.

Initial examination revealed the emission lines of the metal elements found in most meteors. However during a frame by frame inspection of the video a remarkable event was discovered. Within a single video frame the initial spectrum was observed to have undergone a transition into two significantly different spectra.

Video meteor spectroscopy

Video spectroscopy is an important tool in modern meteor observing, allowing the composition of the meteoroid to be determined during its ablation. The equipment used for this observation was a Watec 902H2 Ultimate CCTV camera with a Pentax 12mm f1.2 lens. A 25mm square 300 grooves/mm grating was mounted directly in front of the lens. The video output was fed to a PC with a PCI video capture card, and the images captured using the *UFO Capture* suite.[1]

Figure 1 shows an example of a Perseid meteor with the first-order spectrum also captured on the night of August 12/13. The actual meteor is the bright line at the right of the image and represents what is called the zero-order image. In this image the spectrum is dispersed from blue to red, running from right to left. The star in the frame is Capella. Compared to Capella the image illustrates the brightness of a meteor required to generate a good first-order spectrum. By visual inspection and comparison to other measured spectra the elements emitting the brightest lines can easily be identified in this kind of image.

It is a property of gratings that they also generate higher order

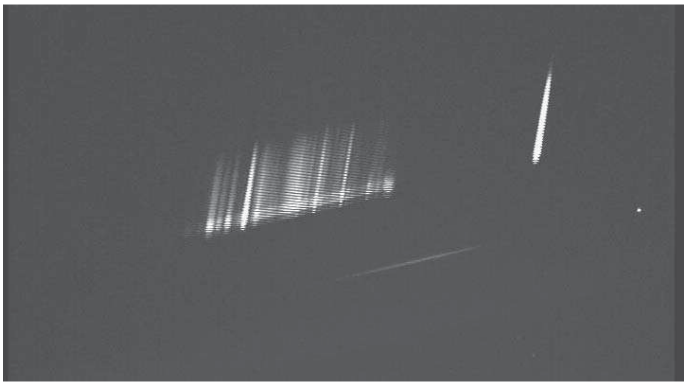


Figure 1. An example Perseid fireball spectrum. The spectrum runs from ~380nm in the near UV to nearly 1000nm in the near IR.

Figure 2. Video composite of bright Perseid meteor spectrum.

spectra. This is a diffraction effect that produces dispersion at twice, three times and so on of the fundamental dispersion as fixed by the number of grooves on the grating. The amount of light from any given source is finite with most being diffracted into the first-order (unless specifically designed for another order). Consequently higher orders of spectra are fainter than the first-order. Another property of diffraction gratings is that they will diffract light on either side of the zero-order image, resulting in a mirror image spectrum with one side usually brighter than the other depending on the exact design of the grating. Diffraction through a grating is a complex matter and a good optics book should be consulted if further information is required.[2]

Recording a higher order means a spectrum of greater dispersion is available for inspection. Generally this is a positive if it has a good signal to noise ratio. In the case of meteor observations, the path and brightness of the meteor must have fortunate characteristics for this to happen.

Fireball observation

The Perseid meteor shower is one of the finest during the year. It offers high rates and regular bright to fireball meteors.[3] The exceptionally bright meteor recorded at 00:38:56 UT on the morning of 2013 August 13 turned out to be a remarkable Perseid fireball.

The video composite is shown in Figure 2 (*cf.* Figure 1. Note the diffraction in the opposite direction due to the fall of the meteor with respect to the grating's particular orientation). The meteor itself fell outside the field of view, to the left. The meteor was exceptionally bright as it generated multiple orders of spectrum. The first, second and part of the third-order spectra span the field of view. This was a very bright meteor exhibiting a terminal flare. The video was inspected frame by frame to see how the spectrum

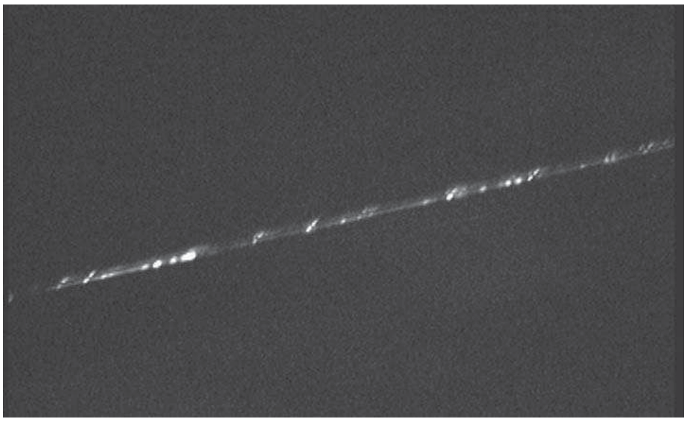


Figure 3. Single video frame showing 1st, 2nd and 3rd order spectra.

changed, if at all, within the flare. During this inspection it became apparent that something extremely rare had been recorded.

Figure 3 shows the video frame of most interest. In the centre of the frame where the second order spectrum lies it can be seen that the spectrum appears to have two distinct compositions, one above the other. This is only revealed as by chance it happened during the time exposure of a single video frame (consisting of two interlaced exposures of 1/50 sec each, giving a 0.04 second interval at 25 frames per second) AND the meteor was bright enough to generate a second order spectrum allowing this level of detail to be seen. This was a remarkable coincidence.

A meteor is a rapid and violent phenomenon. The usual impression of a meteor 'burning up' is not strictly correct. The process is more akin to sputtering, whereby collision with atmospheric atoms results in individual meteoroid atoms being knocked off. The velocity of impact results in high temperatures and pressures resulting in the destruction of the meteoroid and ionisation of the atoms and molecules.[4,5]

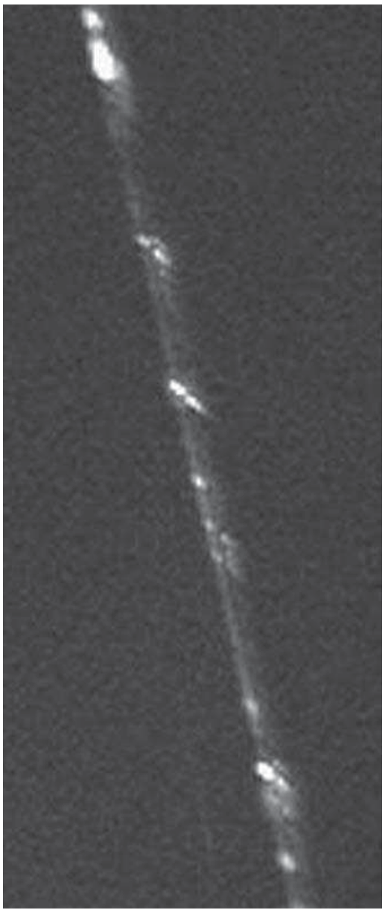


Figure 4a. Close-up of split spectrum.

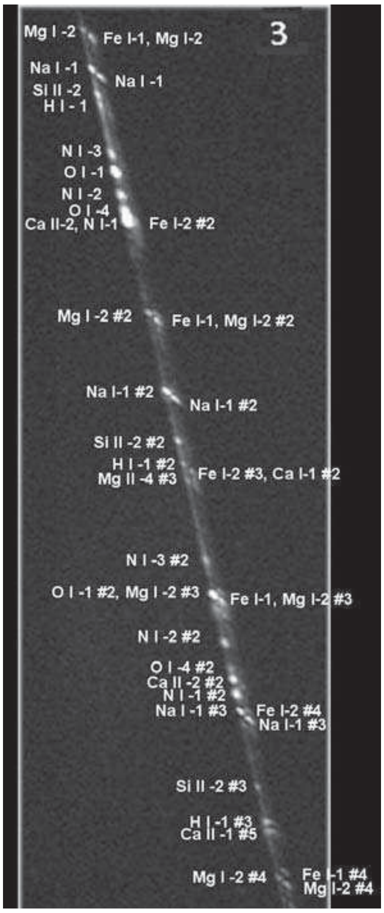


Figure 4b. Spectrum image with additional lines identified *(courtesy of Jiri Borovicka)*.

By considering the kinetic energy alone, a 1g meteoroid travelling at 60km/s (comparable to the speed of a Perseid) is carrying 1.8 million joules of energy. As a comparison this is the same as a motor vehicle (~1000kg) travelling at over 210kph! The forces acting on the meteoroid are extreme. Temperatures around thousands of degrees Kelvin within the meteor head are normal. In work done during the Leonid meteor showers of 1999, 2000 and 2001, models suggest even higher temperatures can be developed, as these are necessary to explain some of the spectrum emission lines observed.[6]

Analysis and discussion

Perseid meteors have been the subject of much spectroscopic examination in the past. A detailed paper by Borovicka & Betlem[7] was consulted for guidance on line identification.

A close-up of the central part of the spectrum is shown in Figure 4a. The spectrum can clearly be seen to have two distinct components. Using the central sections of the image and wavelength list of major lines as given in ref. 7 the spectra were calibrated and plotted. Figure 4b shows a detailed assessment of the lines in this image as provided by Jiri Borovicka. As the spectra were effectively recorded together, no further radiometric correction has been made. The 'upper' and 'lower' spectra are shown in Figures 5 and 6 respectively.

The measured dispersion is 1.2±0.2 nm/pixel. However the effective resolution is dictated by seeing, optical aberrations and geometric processing. The resolution was measured to be 3.8±0.2nm, as determined by the Full Width Half Maximum (FWHM) of the hydrogen line (656nm) in the 'upper' section. Due to this relatively low resolution, wavelengths are only given to the nearest whole nanometre (nm).

The 'upper' section is dominated by the bright lines of magnesium at 518nm and sodium at 589nm. There is also a strong line from hydrogen at 656nm. Many of the smaller features are most probably emissions from iron with others from silicon.

The differences in appearance of the two spectra are significant. The 'lower' section has diminished lines of magnesium (518nm) by 29% with the sodium line (589nm) remaining essentially unchanged. The features around the magnesium line, probably iron, have also reduced. What is striking is the increase in the emission from what was thought to be silicon. The strongest, Si II (638nm), increased by 104%. The strong line indicated at around 770nm is most likely a magnesium emission from the third-order overlapping the second. Due to the optical/geometric distortions this may be blended with the oxygen line at 777nm.

This demonstrates the difficulty in definitive line identification caused by the relatively low resolution and the image properties. In particular this is a problem with order overlap lines where important lines may be misidentified in the incorrect order of spectrum.

Considering the individual effective exposures at normal video frame rate the transition between the 'upper' and 'lower' spectra appears to be only a fraction of this. By examining the enlarged section as shown in Figure 4 the length of trail at the bright sodium line is 9 pixels. Transition from one part to the next is seen to occur over the duration of traversing one pixel. This yields a transition interval of ~0.0044 seconds.

In very high speed meteor imaging using millisecond (0.001s) exposures a shock front within the meteor head can be seen.[8] These features may be of some significance in shaping the behav-

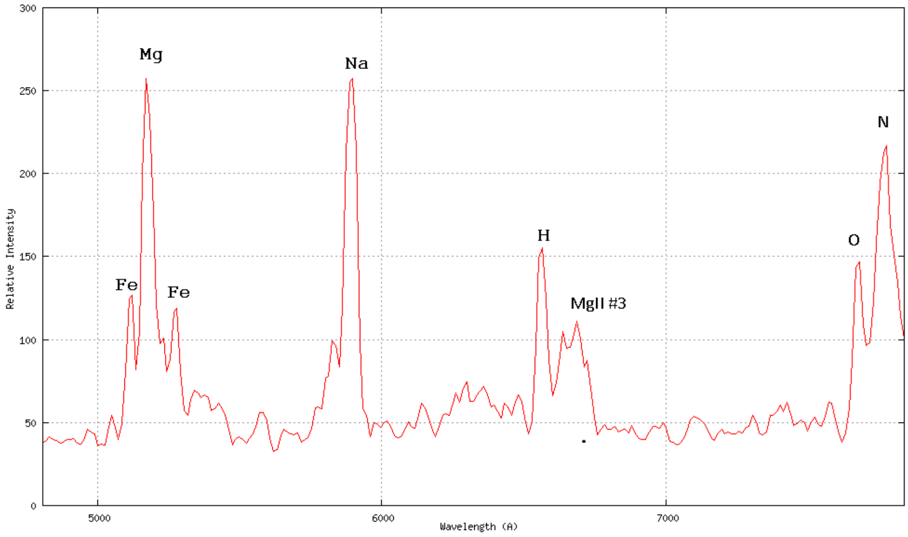


Figure 5. 'Upper' spectrum with major lines identified.

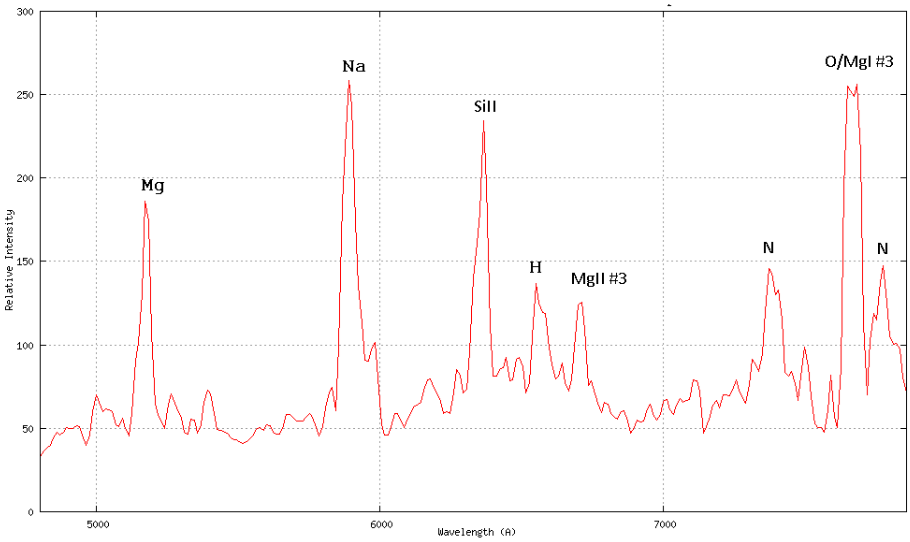


Figure 6. 'Lower' spectrum with major lines identified.

iour of the meteor in its final moments as the remaining part of the meteor emerges from the terminal flare.

As part of the campaigns to observe the Leonid meteor showers in 2000 Borovicka observed a magnitude –13 Leonid fireball.[9] A complete analysis of the emission lines and temperatures expected for this kind of event is presented. (Such observations of the spectra of very bright fireballs are relatively rare). The analysis and interpretation of the Leonid observation in comparison to the observation described here reveals the 'upper' part of the spectrum is the moment of the terminal flare and the 'lower' part is the emission from the surviving meteor in the brief interval before the temperature drops below that required for emission.

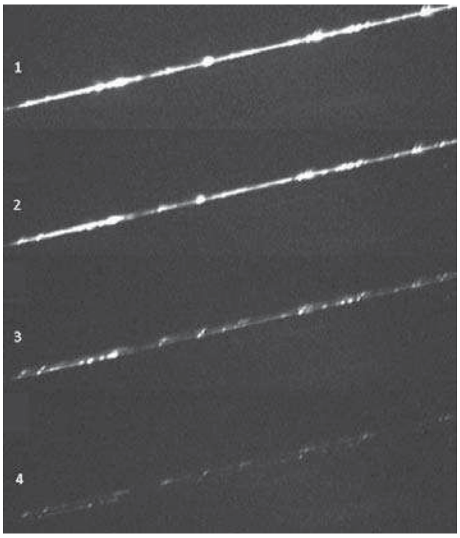


Figure 7. Video frame spectrum sequence.

In Figure 7 the four final individual video frames with the evolution of the dual spectrum at the end of the meteor are shown.

Figures 7-1 and 7-2 show the spectrum before the transition. 7-3 is the frame with the transition spectrum and 7-4 shows the surviving meteor fragment moving forward (downward in this image) and the afterglow remaining above.

Conclusion

The spectroscopic observations reported here are consistent with an afterglow following the terminal flare of the fireball and emissions from the surviving fragment. This observation is one of only a very few of its type and possibly the first of a Perseid fireball yielding a quantitative value for the duration of transition from the bright terminal flare to the end of the meteor, this being of the order of 0.0044 secs. The observation shows that fireballs can exhibit extremely rapid and dramatic variation of their spectra upon reaching the end of their flight as the physical conditions change.

To achieve the highest spectral and temporal resolutions required to fully characterise the spectrum is a significant challenge to video techniques. Care should be taken when considering the composite images as an end product in themselves. It would seem good practice to examine spectroscopic video captures on a frame by frame basis as a matter of course. It is clear that composite images can hide valuable information about short temporal duration events.

This observation demonstrates that video techniques have the possibility of revealing short temporal meteor phenomena. It opens yet another avenue for meteor observers to explore. As ever with a newly developing field, further observations are urgently needed.

Acknowledgments

The author would like to thank Jiri Borovicka for providing additional, detailed line identification and information clarifying the sequence of events and processes in the terminal flare. Also thanks to Michael Wilson and Peter Jenniskens for their additional comments and advice.

Address: 84 Woodwynd, Kilwinning, KA13 7DJ, Scotland. *[William.Ward@glasgow.ac.uk]*

References

1 *UFO Capture* Software, **http://sonotaco.com/soft/e_index.html#ufocv2**
2 Hecht E., *Optics*, Addison Wesley Publishing Co. Inc., 1989
3 *Hbk. Brit. Astron. Assoc.*, BAA, 2012
4 Hawkins G. S., *The Physics and Astronomy of Meteors, Comets and Meteorites*, McGraw–Hill Publishing, 1964
5 Egorova L., 'Modern models of meteoroid fracture', *Proc. Int. Meteor Conf.*, Armagh, 2010, pp 25–27
6 Jenniskens P., 'The mass and speed dependence of meteor air plasma temperatures', *Astrobiology*, **4**(1), 81–94 (2004)
7 Borovicka J. & Betlem H., 'Spectral analysis of two Perseid meteors', *Planet. Space Sci.*, 45(5), 536–575 (1997)
8 Jenniskens P., *Meteor showers and their parent comets*, pp 49–57, Cambridge University Press, 2006
9 Borovicka J. & Jenniskens P., 'Time resolved spectroscopy of a Leonid meteor afterglow', *Earth, Moon & Planets*, **82–83**, 399–428 (2000)

Received 2015 June 17; accepted 2015 September 2

Meteor spectroscopy during the 2015 Quadrantids

Bill Ward[1]

Spectroscopic video observations during the Quadrantid meteor shower 2015 were made with Watec low light level video cameras fitted with 12 mm $f/0.8$ lenses carrying 50 mm square diffraction gratings. Four spectra with adequate signal to noise ratios were captured and the results analysed and discussed.

Received 2015 April 30

1 Introduction

The Quadrantid meteor shower takes place between January 1 to 5 (Rendtel & Arlt, 2014) with a sharp maximum around January 3/4. Due to frequently poor winter weather in the northern hemisphere the observing conditions for this shower are usually not good. Combined with a very sharp maximum it is often missed.

In 2015 the conditions at the observing location in Kilwinning, North Ayrshire were good. There were clear skies during most of the night on January 3/4. However there was some interruption by cloud between 01^h30^m and 03^h30^m UT. The near full moon significantly hampered visual observing but had little effect on the video cameras. A total of 58 meteors were captured by the wide field video system, 44 being Quadrantids and 14 others. 14 Spectra were captured by the spectroscopic video cameras. Of these, four were bright enough to extract useful spectrum graphs from. Those four spectra are the subject of this paper.

2 Equipment and Methods

A battery of four Watec video cameras was deployed. Three were 902H2 Ultimate cameras carrying 12 mm $f/0.8$ lenses with 50 mm square diffraction gratings attached (2×600 groove/mm and 1×300 groove/mm). A fourth camera, a Watec 910 HX/RC was used with a 3.5–8 mm $f/1$ zoom lens. This was set to approximately 7 mm focal length and was used to monitor the meteor shower in general.

The three spectroscopic cameras were mounted on a single tripod and positioned to cover a region approximately 20–30 degrees from the radiant. The cameras were arranged such that the gratings were oriented with the axis of diffraction perpendicular to the anticipated meteor paths. However as the radiant moves with time, some of the meteors improve their dispersion aspect whilst others degrade. This is a problem of all fixed video meteor observing systems. The fields of view also had some overlap. This proved fortunate as some captures were caught on both 600 groove/mm and 300 groove/mm systems. This allowed the best dispersion aspect or most complete spectrum to be selected.

The camera video outputs were taken to PC's fitted with on-board video capture cards, 8 bit PAL, 720×568 pixel frame. The video feed was run through the motion detection software UFOCapture (SonotaCo, 2013).

[1] Email: William.Ward@glasgow.ac.uk

IMO bibcode WGN-434-ward-quadrantids
NASA-ADS bibcode 2015JIMO...43..102W

3 The Spectra

Of the fourteen meteor spectra captured four produced images bright enough to generate spectra with a reasonable signal to noise ratio. Several meteors were captured of one by one or more video camera. The videos with the best spectrum characteristics were chosen. Thus the results here are for two spectra captured with a camera carrying a 600 l/mm grating (Q1 and Q3) and two captured with a 300 l/mm grating system (Q2 and Q4).

Each spectrum is produced in a multi-step process. Firstly the composite video frame is geometrically rotated and de-slanted by the astronomical image processing package, Iris (Buil, 2014). Once in a suitable format it is imported to the spectrum processing software Visual Spec (Desnoux, 2015). The spectrum is orientated thus; the dispersion axis is realigned horizontally with the spectrum lines positioned vertically and running blue to red from left to right along the x-axis. Visual Spec bins the spectral lines to maximise the signal to noise ratio. After calibration the output graph is generated. Calibration is done using the zero order image, where available, and prominent known atmospheric lines such as the Oxygen line at 777.4 nm. This gives a measure of wavelength dispersion per pixel. Once this dispersion factor is determined, it can be used to identify lines by measuring from known lines.

The dispersion for the 300 groove/mm grating on a 12 mm $f/0.8$ lens was measured at 2.28 nm/pixel and for the 600 groove/mm gratings on a similar 12 mm $f/0.8$ lens was measured at 1.13 nm/pixel. The actual spectrum resolution achieved is heavily influenced by the native dispersion aspect and the subsequent geometric manipulation required to re-format the image for spectrum processing. The resolution was determined to be of the order of 3 nm at best by measuring the Full Width Half Maximum (FWHM) of the distinct lines in the blue part of the spectrum in Q1. Q2–Q4 were all of lower resolution. The FWHM of the magnesium line in Q2–Q3 varied between 8 nm and 11 nm. It should also be noted that the Q3 spectrum is very "noisy" due to interline readout noise from the video sensor during the re-orientation process.

However, despite these limitations, the spectroscopic analysis still gives sufficient line information for a relative comparison of the spectra to be made. The video composite frames and resulting spectrum plots of the four meteors are shown in Figures 1 to 8. Several lines of note have been identified and indicated on the spectrum plots.

Figure 1 – Q1 Video composite spectrum image.

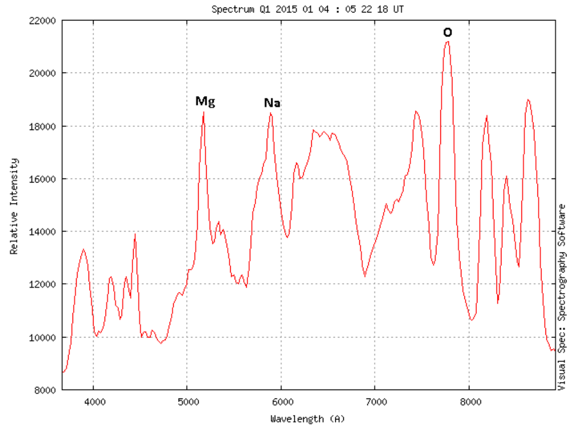


Figure 2 – Q1 meteor spectrum plot.

Figure 3 – Q2 Video composite spectrum image.

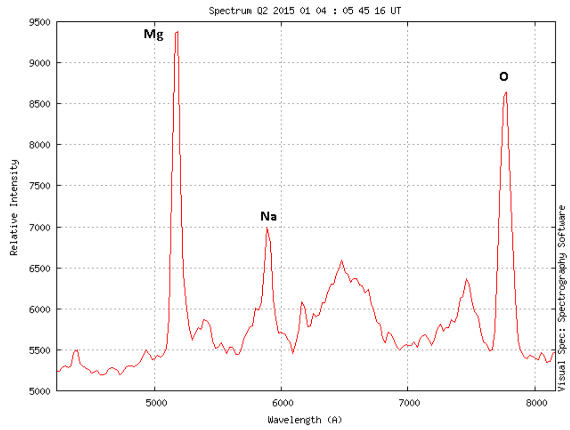


Figure 4 – Q2 meteor spectrum plot.

Figure 5 – Q3 Video composite spectrum image.

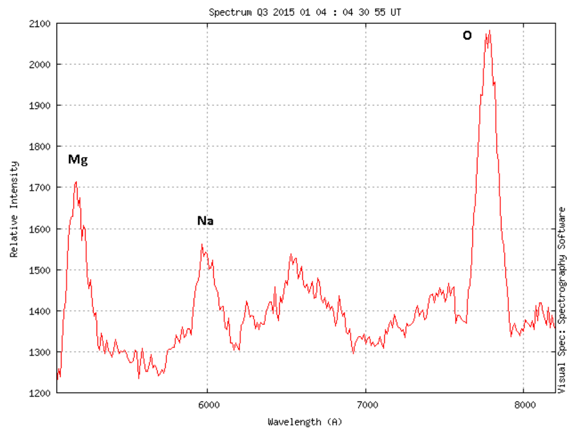


Figure 6 – Q3 meteor spectrum plot.

Figure 7 – Q4 Video composite spectrum image.

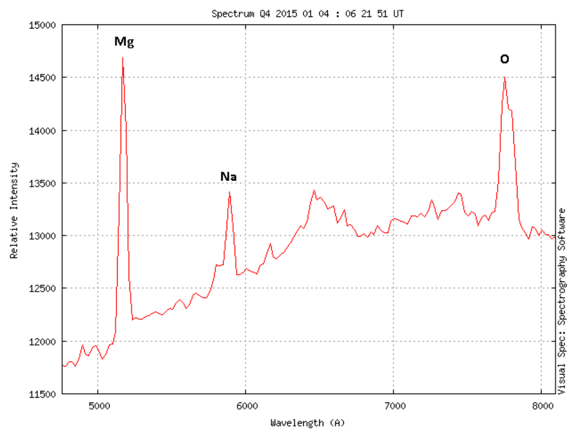


Figure 8 – Q4 meteor spectrum plot.

NOTE: The graphs are plotted without instrument correction. Fundamentally dividing all the graphs by the same flux corrected source would not materially change the result so was felt an unnecessary step in this case.
Initially Q1 stood out as an exceptionally bright capture and was processed first. The others are not in time order due to the way the various frames were selected and processed from each PC.

4 Discussion

Searching the literature revealed only one reference specific to Quadrantid meteor spectroscopy, a 2005 paper by Abe et al. One of the images from that paper is shown in Figure 9.

There was remarkable similarity in appearance of this meteor spectrum image to the negative image of Q1 as shown in Figure 10.

Initially this was taken as confirmation that Q1 was indeed a Quadrantid. However as Q2, Q3 and Q4 were reduced and the final spectra produced, it became apparent that Q1 had a significantly different appearance. In particular, the relative size of the magnesium and sodium lines showed large differences.

Comparing the spectrum plots it can be seen in Q2, Q3 and Q4 that the magnesium lines at $\sim$ 518 nm (5180Å) are significantly stronger (in relative units) than the sodium lines at $\sim$ 589 nm (5890Å). Both the magnesium triplet and sodium doublet are blended together and unresolved at this resolution. By contrast, Q1 has a much more complex spectrum with the magnesium and sodium lines being of similar strength.

The meteor trails were then examined using the UFOAnalyser software (SonotaCo, 2015). UFOAnalyser uses the positional data from the captured video to determine an angular velocity which is then used to calculate a geocentric velocity. It then matches this to the contained database to assign a possible shower membership. Whilst multi-station observations are needed to confirm shower membership without ambiguity it is nevertheless a useful guide when only single station observations are available, as in this case.

Figure 9 – Quadrantid. Figure 1 from Abe et al. (2005).

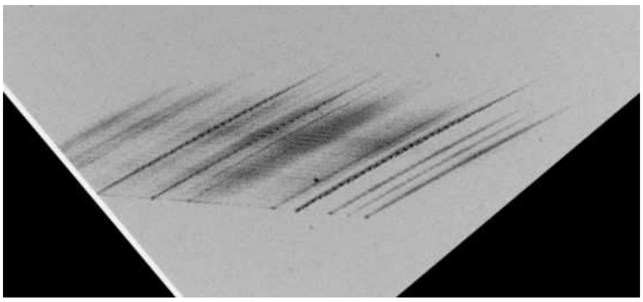


Figure 10 – Negative Quadrantid 2015 image, Bill Ward, Kilwinning, UK.

UFOAnalyser suggested that Q1 was a magnitude −6 sporadic with a velocity much higher than a typical Quadrantid, being approximately 65 km/s as compared to 41 km/s for typical Quadrantids (Rendtel & Arlt, 2014). This is subject to errors in position caused by image aberrations and limited reference stars for the software to conduct the astrometry from. While the result is indicative of Q1 not being a Quadrantid it is impossible to say so without ambiguity.

In ideal circumstances it would be preferable to have multi station observations to determine velocities better and an orbit for each of the captured meteors. However since this was not possible it was taken that alignment with the Quadrantid radiant combined with the velocity assignment generated by UFOAnalyser was sufficient for the other three meteors. Although the spectra of the other three were weaker than Q1 they were significantly different with respect to the magnesium and sodium lines.

If Q1 was not a Quadrantid, do the other spectra indicate that members of the Quadrantid meteor shower show a distinct and unique composition? If Q1 was a Quadrantid being significantly brighter and presumably a larger particle, is this is indicating some change in ablation characteristics with size? This in turn might suggest that there is some threshold at which the spectral signatures change from Q2, Q3 and Q4 to the type displayed by Q1. Borovicka (2005), discusses the distinction between "small" and "large" meteoroid ablation characteristics. His size distinction of around 1 cm is probably too great for direct comparison with the results presented here but does suggest that there may indeed be ablation effects that depend on the size of the meteoroid particle.

During a further online search, a posting on the SonotaCo meteor forum (Maeda, 2015) was noted. This was of an observation of a Quadrantid meteor and its spectrum from Japan by Koji Maeda on 2015 January 4. This is shown in Figure 11.

By processing the spectrum image in the same manner as the others it is clear that it shows very similar magnesium and sodium characteristics as Q2–Q4. It also shows prominent iron emissions in the blue. The spectrum plot is shown in Figure 12.
(It should be noted that Koji Maeda was one of the co-authors of (Buil, 2014).)

5 Conclusions

Four spectra secured during the peak of the 2015 Quadrantid meteor shower have been presented. One of the spectra, Q1, was initially assumed to be a Quadrantid. However, subsequent analysis suggests it may not be due to differences revealed by its computed geocentric velocity, this being 65 km/s, as compared to the typical Quadrantid velocity of 41 km/s (Rendtel & Arlt, 2014). Also, comparing its spectrum to the other three possible Quadrantids, Q2–Q4, showed a significant difference in the relative strengths of the magnesium and sodium

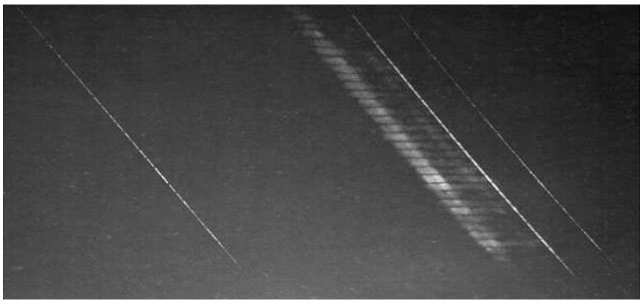


Figure 11 – Quadrantid meteor by Koji Maeda.

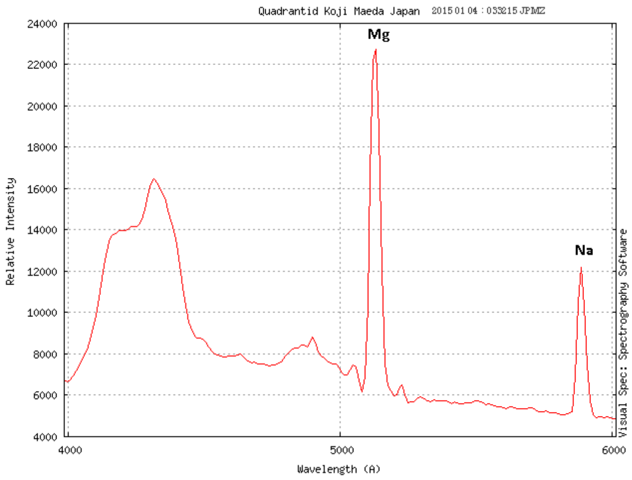


Figure 12 – Meteor spectrum by Koji Maeda.

lines. The spectra of the other three meteors (Q2–Q4) revealed that they appear to have a similar and distinct composition.

An observation of another 2015 Quadrantid from Japan also clearly indicated a stronger magnesium emission similar to that observed in the meteors Q2–Q4.

The observations also illustrate the need for multi station observations to fully remove ambiguity from observations that otherwise may result in possibly erroneous stream assignment/identification.

6 Further Work

Further observations of the Quadrantid shower will be necessary to reveal whether the spectra described here are general to the Quadrantids or perhaps represent a particular sub group of meteoroid particles within the Quadrantid stream.

In order to determine stream membership conclusively multi-station observations are needed. Much spectroscopic work has concentrated on specific campaigns observing showers such the Leonids, Geminids and Perseids. "Lesser" showers have had very little attention until recently and regular long term meteor spectroscopic surveys such as the one now run by the author seem to be much rarer than the usual meteor/fireball networks. For full characterisation combined orbital and spectrum observations are needed.

There is much to explore in meteor spectroscopy which until now has been much neglected due to instrument and technical difficulties. However these difficulties have been overcome to such a degree that regular video meteor spectroscopy is now a viable observational pursuit.

(Since this paper was submitted for review the first successful spectro-orbital observations from the UK have been made by the author and Dr David Anderson. See (Ward, 2015) for details.)

Suggested further reading:
For a detailed examination of Quadrantid orbital and parent body information see (Jenniskens, 2006).

References

Abe S., Borovicka J., Maeda K., Ebizuka N., and Watanabe J. I. (2005). "First results of Quadrantid meteor spectrum". In *Conference proceedings 36th Annual Lunar and Planetary Science Conference, March 14-18, 2005. League City, Texas.* Abstract 1536.

Borovicka J. (2006). "Physical and chemical properties of meteoroids as deduced from observations". In Daniela L., Sylvio Ferraz M., and Angel F. J., editors, *Asteroids, Comets, Meteors, Proceedings of the 229th Symposium of the International Astronomical Union held in Búzios, Rio de Janeiro, Brasil August 7-12, 2005*, volume 229. pages 249–271.

Buil C. (2014). "IRIS Astronomical image processing software". `http://www.astrosurf.com/buil/us/iris/iris.htm` .

Desnoux V. (2015). "Visual Spec spectroscopy processing software". `http://www.astrosurf.com/vdesnoux/howto.html` .

Jenniskens P. (2006). *Meteor Showers and their Parent Comets.* CUP, 357-376 pages.

Maeda K. (2015). "Qua". `http://sonotaco.jp/forum/viewtopic.php?p=37887#37887` . SonotaCo Network Japan Forum.

Rendtel J. and Arlt R., editors (2014). *Handbook For Meteor Observers.* International Meteor Organization.

SonotaCo (2013). "UFOCapture". `http://sonotaco.com/soft/e_index.html#ufocv2` .

SonotaCo (2015). "UFOAnalyser". `http://sonotaco.com/soft/e_index.html#ufoa` .

Ward B. (2015). "Spectro-orbital observation of a sporadic meteor". *WGN, Journal of the IMO*, **43:4**, 106–108.

Handling Editor: Javor Kac

Spectro-orbital observation of a sporadic meteor

Bill Ward[1]

Working in conjunction with members of the Network for Meteor Triangulation and Orbit Determination (Nemetode) arrangements were made to overlap camera fields of view. This was in an attempt to secure spectroscopic observations combined with multi station observations to determine orbits. This has resulted in the first such combined observations to be made from the UK.

Received 2015 May 1

1 Introduction

With the arrival of inexpensive low light level video cameras, numerous meteor observing networks have developed over the last several years and much reported in *WGN*.

Combined with sophisticated software, it is now possible to determine orbits of meteors captured by two or more cameras on a routine basis.

To achieve a fuller understanding of the Earth's meteoroid environment information about the physical composition of the meteors is useful. This can be arrived at by using spectroscopic techniques which allow the elements present in the meteoroid to be determined as it ablates in the atmosphere.

Figure 1 – General arrangement of spectroscopic video cameras.

2 Video Meteor Spectroscopy

Video meteor spectroscopy is an extension of normal video meteor observing by the simple inclusion of a diffractive element in front of the main lens. Normally this is a diffraction grating mounted in a holder that is attached to the lens using a threaded filter holder (Figure 1). The gratings usually have between 300 and 1200 lines per millimetre and are available from any good optical supply company.

Due to the emission nature of the meteor, it effectively behaves as its own slit. That is, it forms a narrow column of light. This is then diffracted by the grating producing a spectrum, should the meteor be bright enough.

For full information on diffraction through a grating, consult (Hecht, 2002).

Whilst simple in principle, sporadic meteors are essentially random events on the sky. If they fall in the field of view, their orientation with respect to the dispersion axis of the grating is also random. (For shower meteors this can be mitigated by pre-positioning the grating dispersion axis with respect of the shower radiant). However for good dispersion a degree of luck regarding the meteor orientation is needed!

The "shallower" the spectrum with respect to the dispersion axis, the broader the lines appear. At the relatively low resolutions available, difficulties in identifying lines through poor wavelength determination/calibration can become a serious problem. The interline read out of the video device can also add artifacts that need to be carefully dealt with.

Once the image has been secured, it is necessary to reduce it to a form that is suitable for processing. This usually involves some geometric re-orientation and then binning to produce a spectrum plot and perhaps a colourised synthetic version for presentations purposes.

3 A Mutual Event

Having both orbital and spectrum data gives a more complete insight into the history and possible source of the meteoroid. To date this has never been achieved from Scotland (UK).

The author has been conducting video meteor spectrum observations since August 2008. Although still subject to the random nature of the meteors the quality of the spectra obtainable has improved considerably with the use of good quality 12 mm $f/0.8$ lenses and 600 lines/mm fused silica gratings.

Through the Meteor Observers Forum[a] contact was established with the coordinator and members of the NEMETODE Video Meteor Observers Group[b]. A comprehensive map of NEMETODE stations is maintained on their website. Unfortunately due to buildings, security lights, and street lighting issues the area of sky accessible to the author did not overlap with existing coverage by NEMETODE stations. An approach was made to the two nearest stations about the possibility of re-positioning their cameras (David Anderson, near Girvan and Dennis Buczynski, Tabartness).

After some seven years of experimenting (Video Atmosphere and Meteor Observation System, VAMOS and the Kilwinning Spectroscopic Survey for Meteors,

[1]Email: `William.Ward@glasgow.ac.uk`

IMO bibcode WGN-434-ward-sporadic
NASA-ADS bibcode 2015JIMO...43..106W

[a]`http://meteorobserver.proboards.com`
[b]`http://www.nemetode.org`

Figure 2 – Meteor and spectrum captured by B. Ward, Kilwinning, Scotland. Camera: Watec 902H2 Ultimate. Lens: 12 mm $f/0.8$, grating: 600 lines/mm (fused silica substrate).

Figure 3 – Meteor image captured by David Anderson, Low Craighead near Girvan, Scotland. Camera: Watec 902H2 Ultimate. Lens: 12 mm $f/0.8$.

KiSSMe) with different cameras, lenses, gratings, computers and all manner of accessories, there was now the possibility of achieving a step forward in routine meteor observing.

Success came more quickly than anticipated! In only a month of operation a mutual event was caught on the morning of the 2015 April 10 at $00^h58^m37^s$ UT. (In practical terms actually a very few hours' worth of observing!) After noting the spectrum, David was emailed and he confirmed he had got it! Figures 2 and 3 show the meteor spectra. (It was found out that Dennis had not re-orientated his camera and so did not catch the event)

4 Analysis

It was unfortunate that the meteor was relatively a bit "shallow" to the dispersion axis. Comparing the spectrum to existing examples the main lines can be identified. In this case there were prominent magnesium and sodium lines. To fit the other lines, a wavelength comparison is made using the National Institute of Standards and Technology (NIST) list as a reference. Once a wavelength calibration has been determined, the spectrum can be graphed and a synthetic version generated (Figures 4 and 5). To correct for instrument response, the spectrum has been divided through by a flux corrected black body response of 4000 K. This temperature was chosen to approximate the physical temperature of the meteor.

The spectrum shows the lines of magnesium at 518 nm (green), sodium at 589 nm (yellow) and oxygen at 777 nm (near infra red but coloured deep red for illustration). There are also bands of unresolved iron lines in the blue and green part of the spectrum. The spectrum indicates a stony mineralisation with some iron content.

Using the multi-station tracks a ground track and orbit were determined by processing the information through UFOOrbit (Figures 6 and 7).

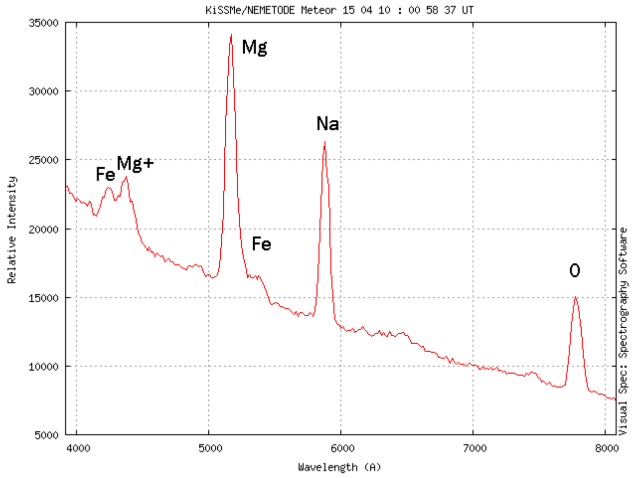


Figure 4 – Instrument response corrected spectrum graph.

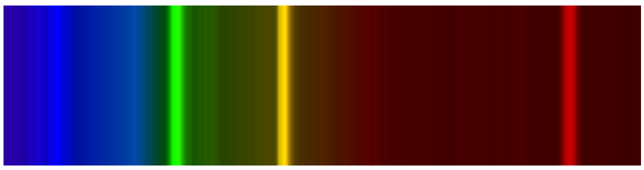


Figure 5 – Colourised synthetic spectrum.

The orbit has an inclination of approximately 10 degrees and an aphelion within the asteroid belt. This suggests the meteoroid was of asteroidal origin, perhaps a tiny fragment of a long past collision.

5 Conclusion

A mutual event has been recorded by two stations, one of which was operating a spectroscopic system. The orbit and spectrum reveal the stony (iron) composition and its source from within the asteroid belt. It is the first time that such a multi station spectro-orbital meteor observation has been conducted from Scotland (UK).

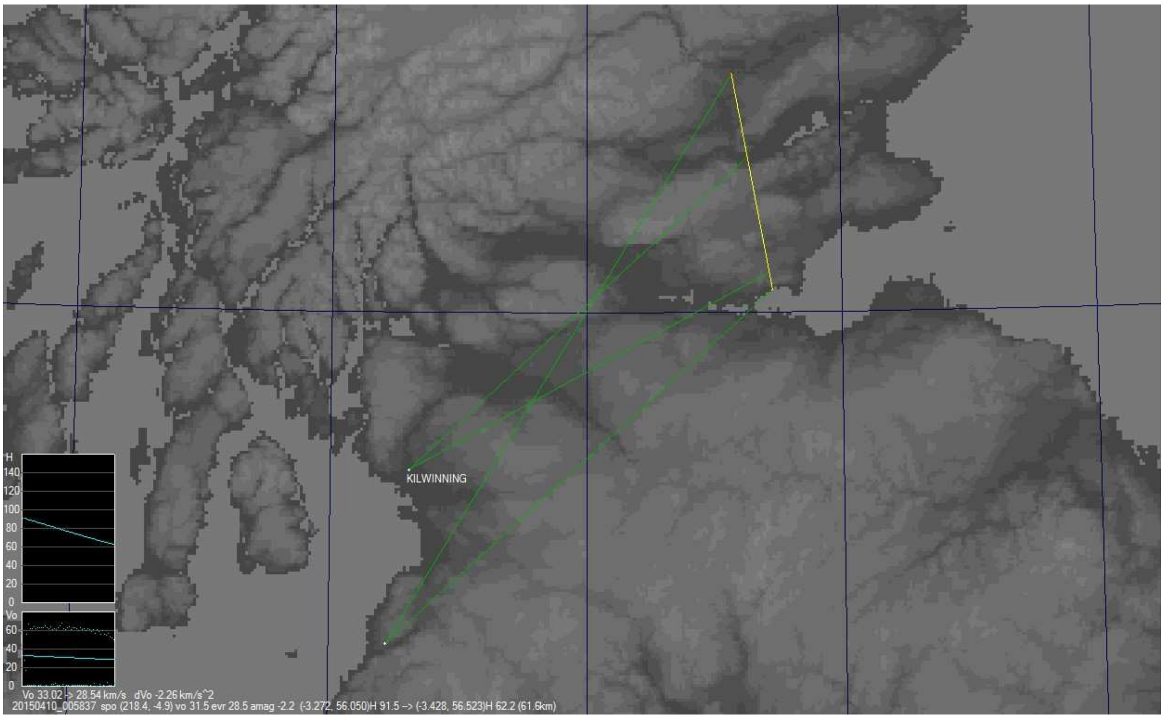


Figure 6 – Ground track of meteor as determined from the two observations.

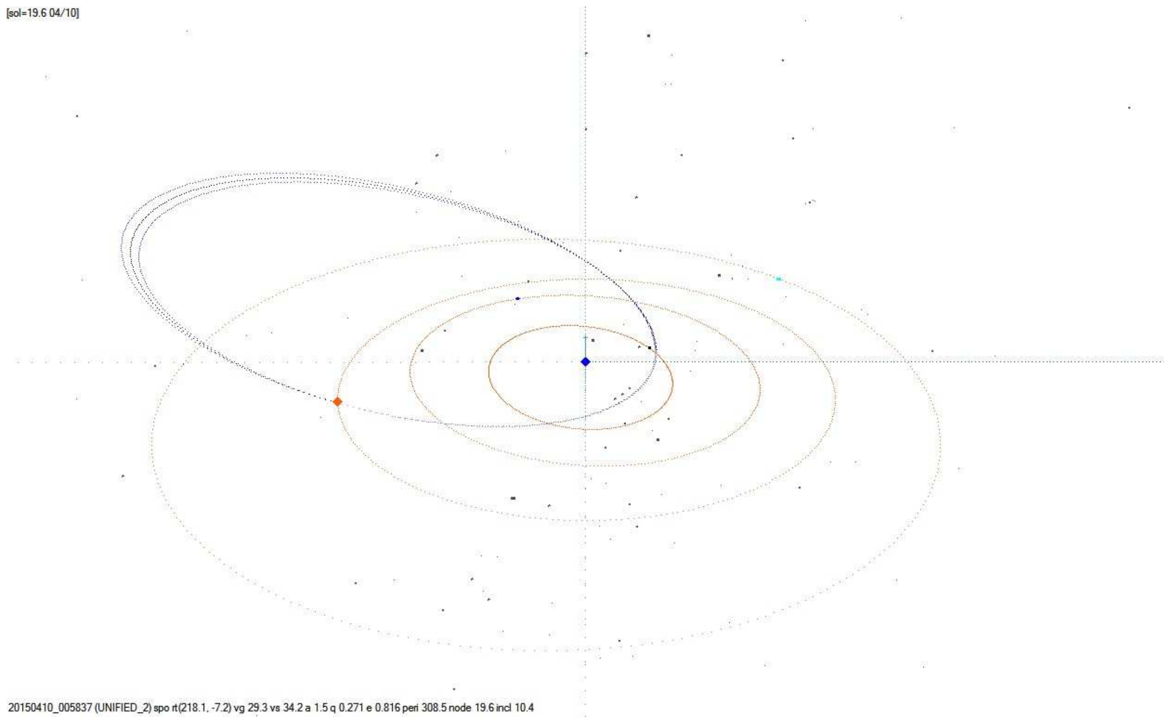


Figure 7 – 3D perspective view of the meteoroid orbit.

Acknowledgements

Observations such as this are highly collaborative ventures. Each station is individually specialised but it is only by working in tandem that these results are achievable. The author would like to express his thanks to David Anderson for his efforts and cooperation. Thanks also to Nemetode Network co-ordinator William Stewart for his support and for carrying out the orbital analysis. This work would not have been possible without the help and support of Dr Marc Sorel and Dr David Muir of the School of Engineering, University of Glasgow.

References

Hecht E. (2002). *Optics*. Addison Wesley, 476 pages.

National Institute of Standards and Technology (NIST). "Basic atomic spectroscopic data – finding list". `http://physics.nist.gov/PhysRefData/Handbook/Tables/findinglist.htm` .

Handling Editor: Javor Kac

Video Meteor Spectroscopic and Orbit Determination Observations. April 2015 to April 2016.

Bill Ward. 84 Woodwynd, Kilwinning, KA13 7DJ, Scotland, UK. 6th July 2016.

Abstract. This paper reviews the combined video meteor spectroscopic observations of the Kilwinning Spectroscopic Survey for Meteors (KiSSMe) and the related mutual capture, multi video station orbit observations from the Network for Meteor Triangulation and Orbit Determination group (NEMETODE) in the period between April 2015 and April 2016. A total of eleven mutual events were captured. A brief comment is made about the main lines in each spectrum and the orbital elements are given for eight of the meteors.

1: Introduction.

Many observers, both amateur and professional, utilise the compact Watec CCTV cameras. These cameras have become particularly popular due to good performance at relatively low cost. The rapid growth in the number of observers using video techniques has led to the formation of many groups undertaking multi station observations in order to obtain orbital information about meteors.

One such group is the Network for Meteor Triangulation and Orbit Determination (NEMETODE), Ref 1. At the time of writing, NEMETODE has multiple stations with 57 cameras in operation across the UK, Ireland and France. Members of the NEMETODE group use a variety of systems including Watec, Genwac and KPF video cameras

Video meteor observations have been carried out at Kilwinning since 2004. In 2008 a decision was made to develop spectroscopic techniques as there seemed to have been very little done in this field with regards to the use of video systems. Initial results indicated that whilst of limited resolution a sufficient number of spectra could be captured to contribute viable results. The first results of this effort were presented at the International Meteor Conference held in Armagh 2010, Ref 2. Due to ongoing improvements in equipment over time the camera system is now operated in a "survey mode". That is, the cameras in the system now use lenses carrying gratings at all times to try to capture as many spectra as possible.

This review clearly demonstrates the advances now being made in (amateur) meteor astronomy. From orbital studies it is possible to say where the meteoroid "came from", thus possibly leading to a determination of a parent body. With spectroscopic analysis an outline of the meteoroid's composition can be made, saying what the meteoroid was "made of" and perhaps indicating whether cometary or asteroidal. By combining the multi station orbital observations with spectroscopic observations there is the ability to gain a much more complete insight into the Earth's meteoroid environment.

Until recently such work was only possible by a few established professional observatories. This is no longer the case!

2: Spectroscopic Observations.

The spectroscopic observations were made with Watec 902H2 Ultimate and Watec 910 HX/RC cameras. The cameras use 12mm f0.8 lenses and carry 600 groove/mm or 830 groove/mm fused silica transmission gratings. Gratings produce an almost linear dispersion making them ideal for this application. However due to the nature of light diffraction through a grating, multiple spectra, called orders, are produced. This can sometimes be problematic as there can be overlap between spectra causing difficulty in interpretation. Only one spectrum in this review has a significant issue with this (KSSM/NEM #010).

Another problem encountered when using a grating dispersing element is the orientation of the meteor with respect to the grating axis. If the meteor falls exactly across this axis the dispersion will be as large as it is possible to be with the given optical configuration. However, most meteors appear at an angle that is less than this. The result is a tilted spectrum which requires further processing as described below. The net effect is that the corrections tend to broaden the spectrum lines thus loosing effective resolution.

2.1: Outline of processing.

An example of a composite image produced by the software used to detect the meteor spectrum is shown in figure 1.

Figure 1. Composite video meteor spectrum image. KSSM/NEM #005.

In figure 1, the “blue” end of the spectrum is towards the right and the “red” is to the left. This example is quite unusual as it is essentially complete. The fortunate position of the meteor with respect to the optical axis has meant the entire span of the spectrum from the near UV to the near IR has been captured. Due to the spatially random occurrence of meteors on the sky capturing only a part section of the spectrum is much more typical.

Briefly, before producing a spectrum graph the image requires some pre-processing. The geometrical image processing is carried out with the IRIS software, Ref 3. The spectroscopic processing requires that the spectrum runs blue (shorter wavelengths) to red (longer wavelengths), left to right. This is the opposite of what happens to have been captured in figure 1. Therefore it is necessary to rotate the spectrum to the required orientation. Once in the appropriate orientation the spectrum image itself often needs to be "de-slanted" so that the spectrum lines are vertical. The de-slanting process broadens any line present reducing the resolution. Once in the correct format the image can be imported into the spectroscopic analysis software Visual Spec for reduction, Ref 4.

Due to the design of commercially available CCTV lenses and the broad sensitivity of the monochrome sensor used in the Watec camera defocus is problem at the extreme ends of the spectrum. This is especially troublesome at the far blue end where prominent lines of magnesium and calcium, as in this example, appear bloated out of focus. A similar but less dramatic effect can be seen at the near IR end of the spectrum (out to >900nm).

Being commercial CCTV lenses for use in security work they are simply not designed to work at the extremes of wavelength under these particular operating conditions. By trying to re-focus, the problem is not improved because the glasses in the lenses cannot form a fully corrected image across such broad wavelength range. Any slight improvement at one end of the spectrum results in even greater degradation at the other. The best focus is generally achieved in the blue/green part of the spectrum.

With the limitations imposed by the number of lines on the transmission grating and the focal length of the lenses used the practical resolution achieved is quite low. Combined with variable observing geometry it is in most cases the order of a few nm (As measured by the full width half maximum on various representative lines). This is insufficient to resolve the closely spaced emission lines of elements such as magnesium (a triplet around 517nm) or sodium (the famous doublet around 589nm).

Nevertheless some spectra can show considerable detail.

3: The Spectra.

This review considers spectra that were obtained between April 2015 and April 2016. This period is entirely arbitrary and was based on the occasion of securing the first multi station and spectrum observation from the UK on 10th April 2015, Ref 5. It should also be remembered that meteor spectra consist of a number of emission lines, some of which are related to the composition of the meteoroid itself, whilst others are related to the upper atmospheric gases with which it is colliding

3.1: Spectrum Graphs.

Due to the software used the wavelengths are displayed as Angstroms on the graphs. The Angstrom is not an SI unit but it is frequently favoured in many spectroscopic applications through common use. 1A is equal to 0.1nm. Thus 5000A is equal to 500nm. The Angstrom will be used in the description text to minimise confusion when referring directly to the graphs.

An inherent feature of the sensors used in the Watec cameras is that they have a wavelength dependent sensitivity. That is, they are more sensitive to red and near IR light than to blue. To correctly portray the spectrum it must be adjusted to deal with this variation. The most important is an instrument flux correction. This is normally achieved by dividing the spectrum by known spectrum flux standard. The spectrum from the star Vega is often used. Whilst this generates a corrected spectrum the graphing produces a spectrum that can be quite steeply curved. This in effect "compresses" the visibility of some lines.

To present a more uniform appearance the spectra have been normalised, that is numerically set to a value of 1.000, in part of the spectrum where there are no major lines present. For clarity of exposition the corrections described have not been applied to the spectra as presented. For a comparison to older photographic techniques and results the review by Ceplecha is to be recommended, Ref 6.

The spectra themselves illustrate some of the difficulties already mentioned. Each one spans a different range of wavelengths, illustrating the point that few captures ever show the whole spectrum.

The spectrum graph of KSSM/NEM #001 has its main emission lines annotated. Since these are the most common ones found in meteor spectra they can be used as a guide to the other graphs.

Notes on the individual spectra are given. Line identification was done by comparison to known meteor spectrum lines and by comparison to the emission spectrum line database included with the Visual Spec software, Ref 7. Once the spectra have been inspected it will be noted that most contain the same well known elements. This gives the subtle yet profound message that the Earth and everything on it are all made of the same “stuff” as our cosmic neighbourhood!

Figures 2 to 12 show the eleven spectra obtained.

4: The Meteor orbits.

The orbital data was derived from observations made by members of the NEMETODE group. The UFO Capture suite was used to capture and process the images and produce the orbits, Ref 7.

Examples of orbit plot and ground track map are shown in Figs 13 and 14.

Figure 13. Example plan view of calculated KSSM/NEM #005 orbit produced by UFO Orbit. Multiple orbits are shown indicating the orbital solutions obtained from the different stations. The blue orbit in this diagram, is the "unified orbit". This is the orbit for which the orbital elements have been tabulated. It is derived from the actual observational data and incorporates various dynamic parameters described in the UFO Orbit Manual., Ref 8.

Figure 14. Example ground track map for KSSM/NEM #005, produced by UFO Orbit, showing the meteor (crossing the Firth of Forth) and the three observing stations.

Eleven mutual events were captured. KSSM/NEM #001 was the first multi station/spectroscopy event recorded from the UK and is detailed in Ward (Ward. 2015).

Three meteors could not have their orbits determined. Whilst detected by multiple stations, either poor observing geometry or only very small fragments of the meteor image prevented this. These are included for completeness as a spectrum was captured for these events. Indeed it is great pity that this applies to KSSM/NEM #008. This was very detailed and complete spectrum. It would have been an excellent result to obtain an orbital solution for this particular meteor.

It should also be noted that the orbits presented do not represent definitive orbits. That is, the number of recording stations was either the absolute minimum of two or the respective observing geometry was poor resulting in limited astrometry. Nonetheless within these limitations there is a wide variation in orbital elements illustrating the fact that the Earth encounters meteoroids from many directions in space.

4.1: Orbital elements.

A summary of the calculated orbital elements is shown in Table 1.

Table 1: Orbital elements.

Orbital elements notes:

a Semi major axis in AU

q Perihelion distance in AU

e Eccentricity. (Dimensionless)

ω Argument of perihelion (degrees)

Ω Longitude of ascending node (degrees)

i Inclination of orbit with respect to Earths orbital plane (degrees)

T(j) Tisserand parameter.

The Tisserand Parameter T(j) is a useful dynamical parameter that is a measure of the interaction of a small body and a planet. In most cases this is referred to Jupiter. Determining the T(j) involves the small body's semi major axis, eccentricity and inclination. It can be used to classify small bodies and is included here as an indication of the possible source of the meteoroids observed. For example members of the Jupiter family of comets have a T(j) of between 2 and 3 whereas most asteroids are greater than 3. See Jewitt, Ref 8.

Notes: The letter u in the T(j) column indicates the orbit was not determined and hence undefined.

Considering Table 1, the T(j) of #001, #006 and #007 could suggest an asteroidal origin. While #003, #005, #009 and #010 could be cometary origin. #011 has an exceptionally low T(j) but given the very large semi major axis and high inclination this orbit may not be reliable.

It should be cautioned that T(j) is not a guarantee of any particular association and is only a guide.

The utilities available within the UFO Capture suite allow stream identification. The eight meteors for which an orbit was determined, however, were all classed as sporadic meteors.

5: Conclusions.

Over the past few years meteor astronomy has undergone both something of a renaissance and revolution. The combination of powerful software and commercially available low light level cameras has given the meteor observer a new arsenal. Previously, spectroscopy was generally only attempted when the chances of success were considered high, during a major meteor shower for example. Occasionally the chance capture of a fireball spectrum would produce exceptional results.

This was the norm for several decades. With the low cost and efficiency of modern cameras it is now possible to operate in continuous "survey mode", yielding vastly more data and significant new results. The observations presented here illustrate that multi technique and multi station observations can give an insight into the Earth's meteoroid environment that has been hitherto impossible to achieve.

In this field a suitably equipped observer can produce results that are important for the future evolution of meteor astronomy. The results may have even greater significance if they are contributed to a centrally maintained and accessible database. Such databases will ultimately allow statistical examinations of meteors' physical properties once sufficient numbers of such observations have been obtained. Some efforts have already been made but the way forward needs further investigation, Rudawska, Ref 9.

Some of the spectra here certainly present broad similarities but yet have subtle differences. Comparing these results to the older photographic taxonomic descriptions reveals that video spectra, even at fairly low levels of resolution, can provide comparable detail. Rendtel, Ref 10. As the technology continues to advance and the number of spectroscopic observing stations increases it is likely that some new classification scheme will be needed. This represents a considerable challenge in its own right.

However it may be that the inherent variation in the spectra means that a simple scheme may not be possible. Other methods of analysis will be needed. Such element ratio techniques are discussed in the review by Borovicka, Ref 11 and are used by professional meteor scientists.

6: A Final Thought.

The Earth is bombarded daily by many thousands of meteoroids. After being in their orbit around the sun, possibly for many thousands of years, maybe even longer, they finally encounter the Earth. After such a long life it is remarkable to consider that it is only in the final seconds they reveal their true nature to us in that last flash of light, a glorious shooting star.

Acknowledgements.

The author would like to thank all of the NEMETODE group members who have offered their observations and great support.

The observers who contributed their video observations were David Anderson, Dennis Buczynski, Jonathon Jones, Glyn Marsh, Graham Roach and Ray Taylor.

Also, thanks to Dr David Asher of the Armagh Observatory for checking the Tisserand parameters.

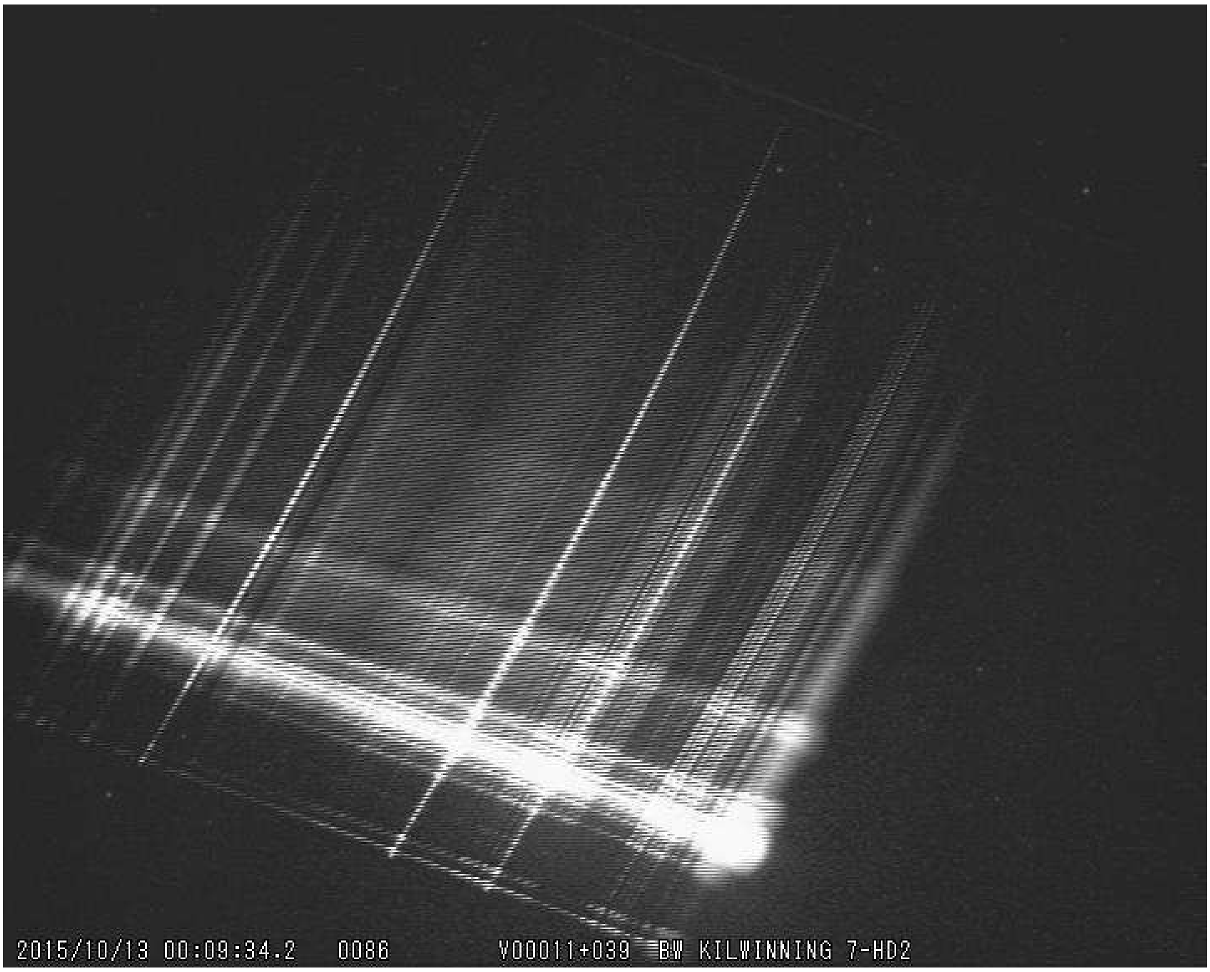
The author would like to especially thank Alex Pratt and William Stewart for their own observations and producing the orbit data and plots and thanks again to Alex for his review and helpful comments on the original text.

Table and Figures.

Table 1. Orbital elements.

KSSM/NEM	Date_Time(UT)	a	q	e	ω	Ω	i	T(j)
001	20150410_005837	1.5	0.271	0.816	308.5	19.6	10.4	4.095
002	20150421_015752							u
003	20150911_022719	2.8	0.969	0.649	205.4	167.8	4.6	2.221
004	20150927_031602							u
005	20151013_000934	2.5	0.395	0.841	288.8	199.1	0.7	2.832
006	20160215_043649	1	0.192	0.808	323.3	325.7	12.7	5.714
007	20160215_052857	0.7	0.388	0.439	351.3	325.7	156.7	6.829
008	20160218_025142							u
009	20160225_013519	3.6	0.989	0.726	178	335.7	28.3	2.519
010	20160210_050202	2.7	0.957	0.646	155.3	349.8	49.3	2.815
011	20160420_023041	128.5	0.534	0.996	266.4	30.2	75	0.492

Figure 1. Composite video meteor spectrum image. KSSM/NEM #005.



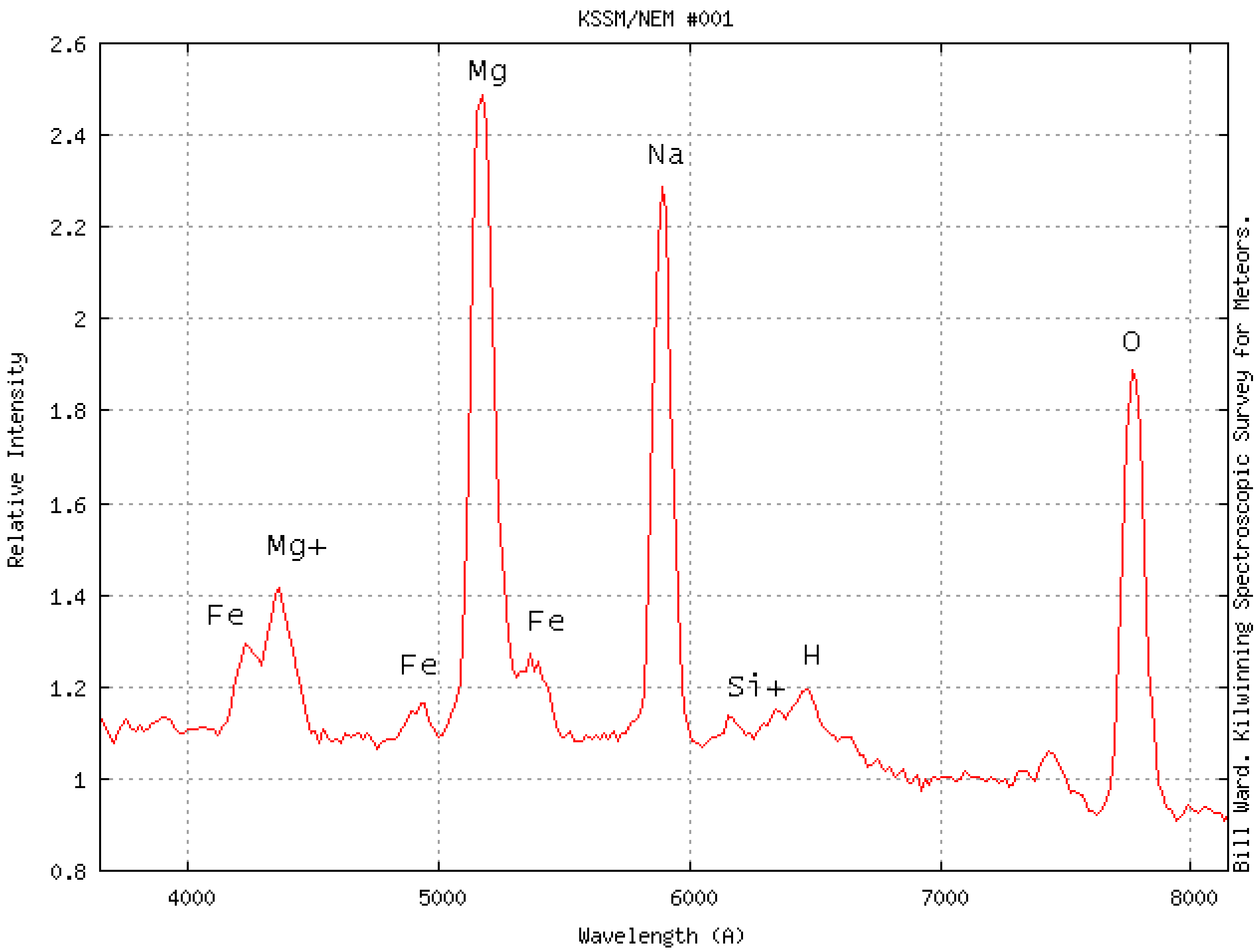


Figure 2. Spectrum Graph KSSM/NEM #001. 20150410_005837UT

Figure 2 notes. This spectrum shows fairly typical element emission lines at the normal level of resolution using the type of camera/lens/grating described in the text. The three most prominent lines are of the magnesium (Mg) triplet at 5175A (green), sodium (Na) doublet at 5893A (yellow-orange) and oxygen (O) at 7774A (near IR). Other lesser peaks can be identified with ionised magnesium (Mg^+) at 4481A, several weaker iron (Fe) lines at 4326A, 4921A and 5270A, ionised silicon (Si^+) at 6359A and hydrogen (H) at 6563A.

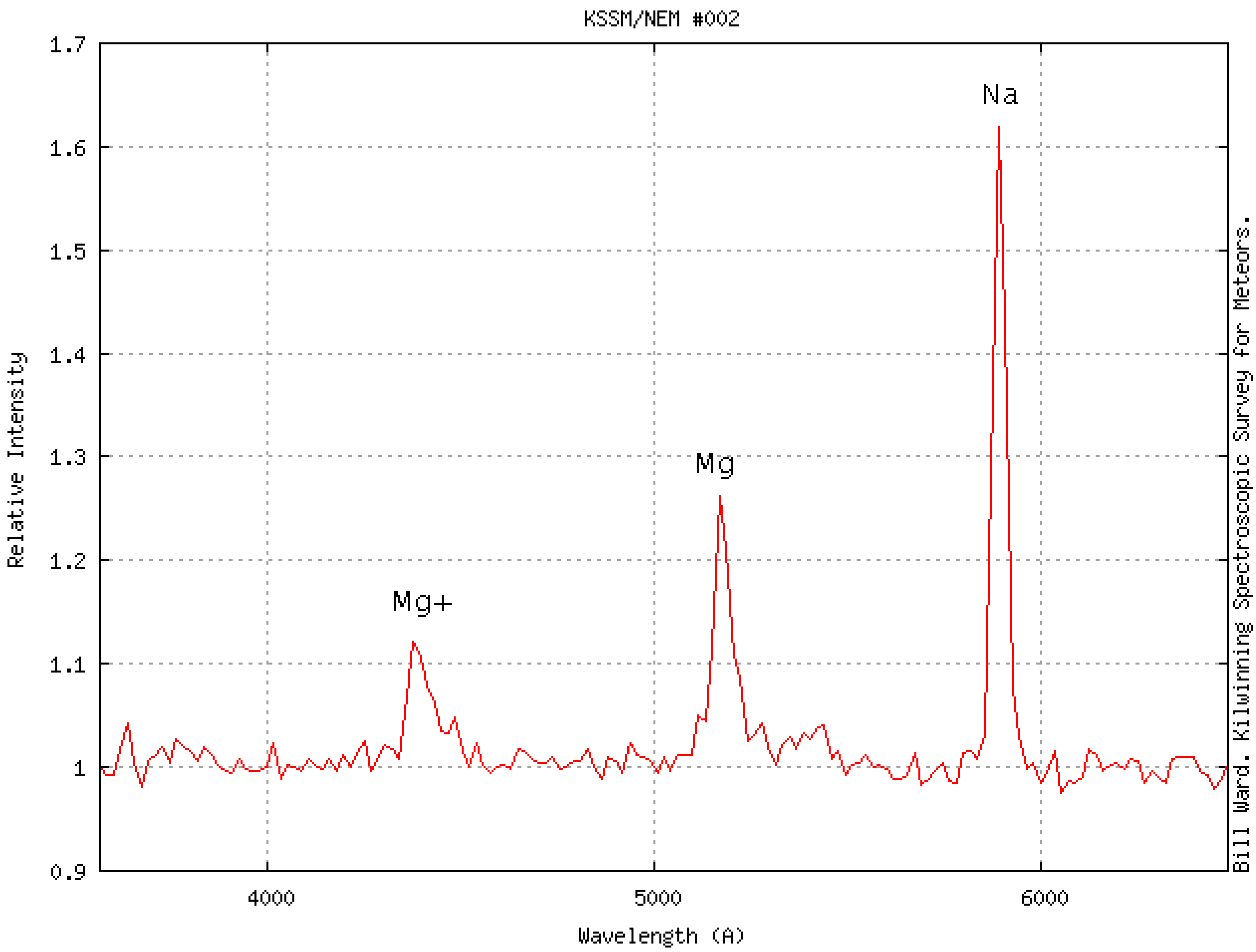


Figure 3. Spectrum Graph KSSM/NEM #002. 20150421_015752UT

Figure 3 notes. This spectrum is rather "noisy" and was relatively weak. Many of the smaller "peaks" are artefacts from the pre-processing stage. These peaks are caused by the raster scan nature of the video output. With re-processing these can be exaggerated and appear as physical features in the spectrum. Great care must be taken when encountering this type of spectrum. It is easy to fit reference lines to non-existent lines when there are many false peaks. The strongest line is of Na (5893A). The other two peaks are Mg^+ (4481A) and the Mg triplet (5175A).

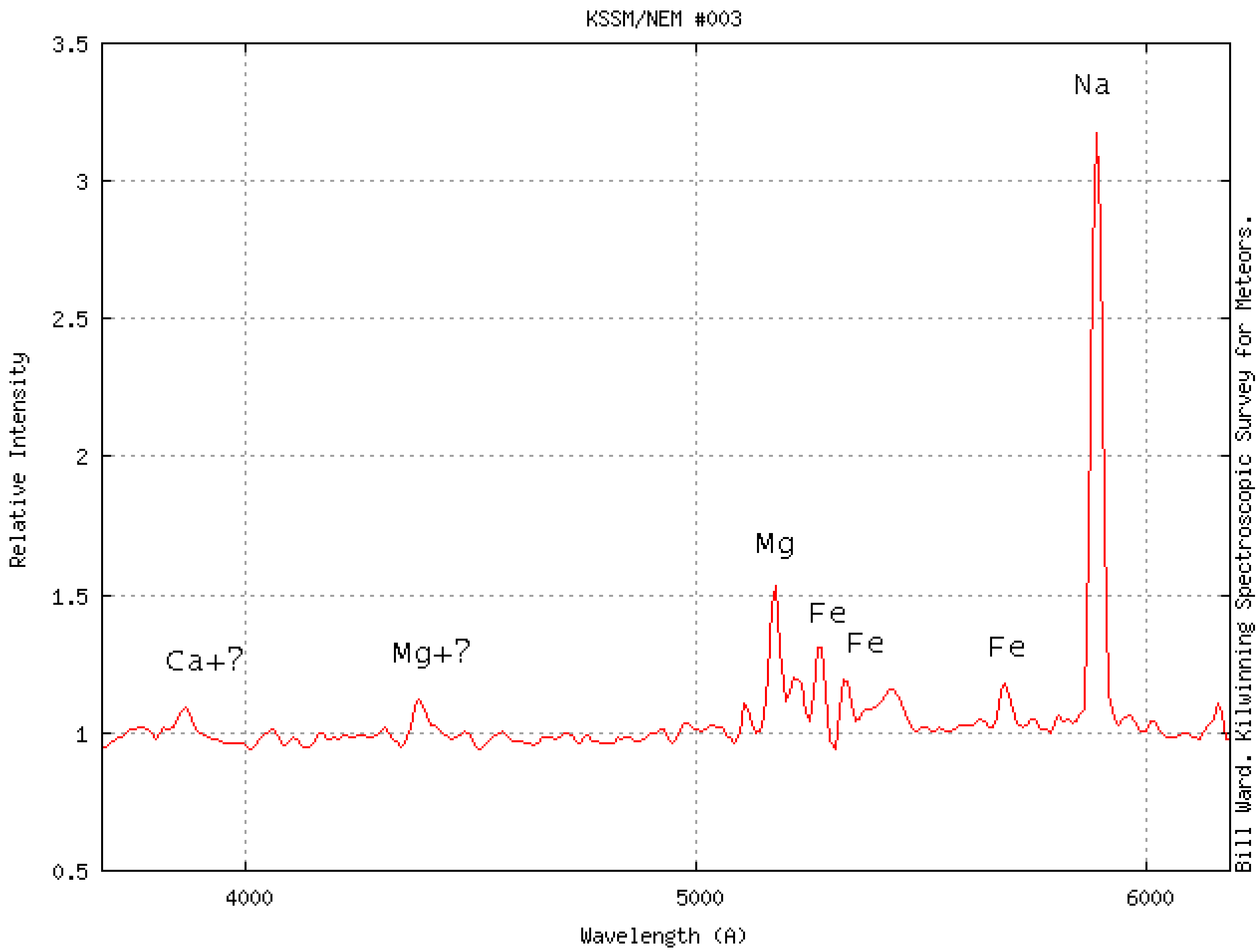


Figure 4. Spectrum Graph KSSM/NEM #003. 20150911_022719UT

Figure 4 notes. Here there is a very strong Na (5893A) signature compared to the other lines. The Mg (5175A) and Mg+ (4481A) lines are much weaker but although weak several Fe lines are visible in the green part of the spectrum between 5228A and 5615A.

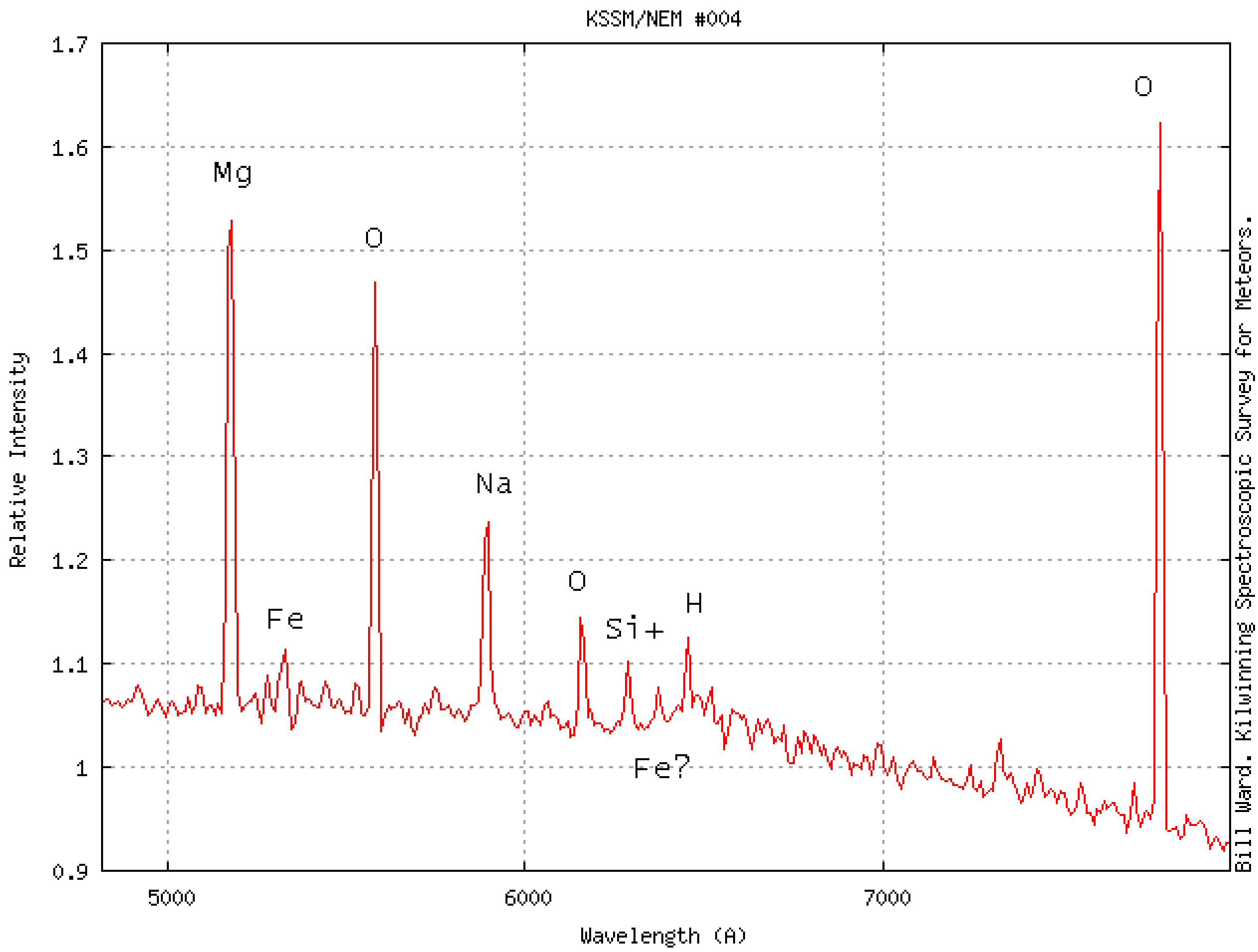


Figure 5. Spectrum Graph KSSM/NEM #004. 20150927_031602UT

Figure 5 notes. Due to the good dispersion geometry the resolution of this spectrum is better than usual. The presence of the forbidden oxygen line at 5577A indicates this was a fast meteor. In this case the Mg line 5175A is stronger the Na 5893A line. There are line from O at 6157A, Si^+ at 6359A and H at 6563A.

The slight "run off" of the spectrum longward of 6500A is due to vignetting being emphasised in the de-slanting process during reduction.

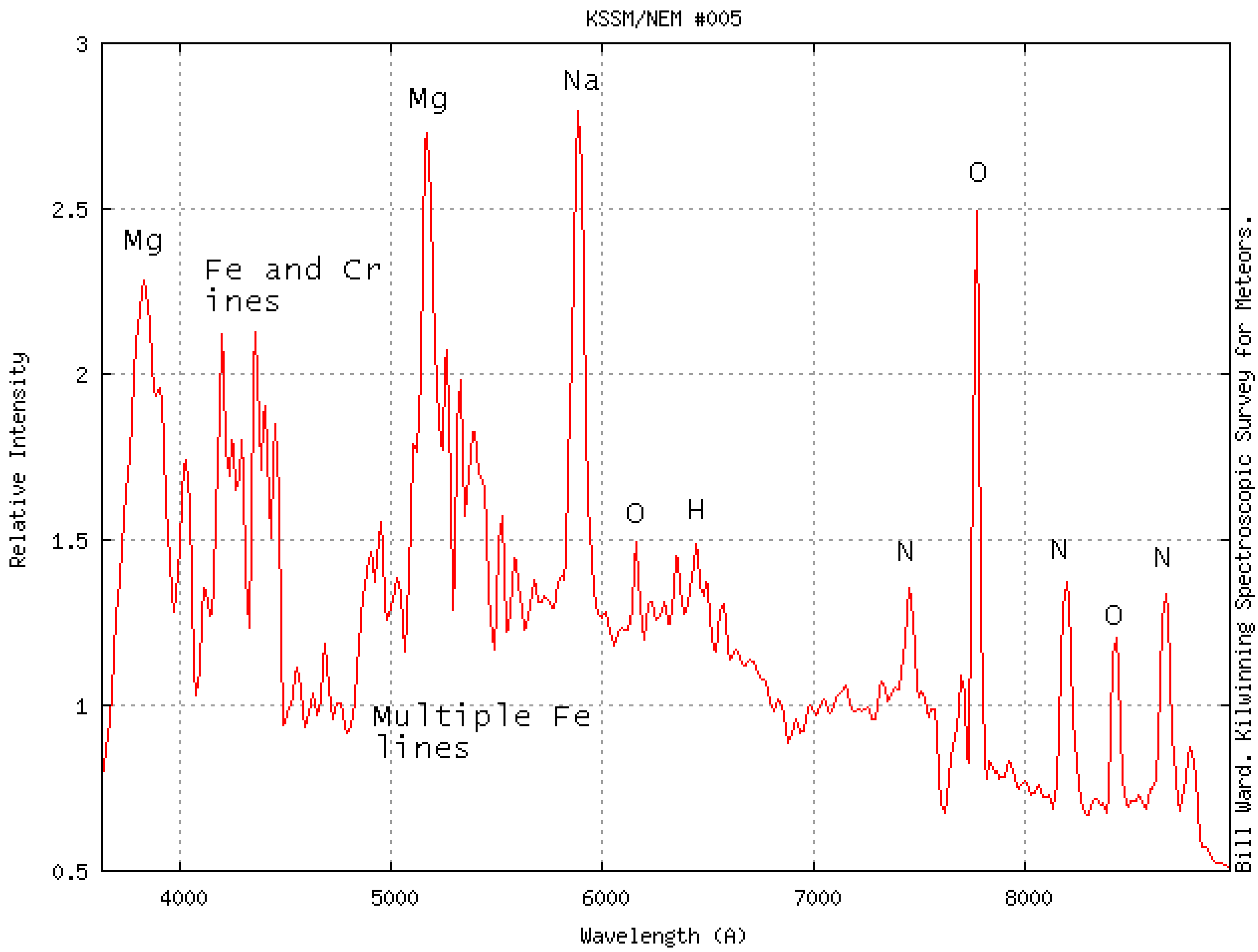


Figure 6. Spectrum Graph KSSM/NEM #005. 20151013_000934UT

Figure 6 notes. Good dispersion and spanning a wide wavelength range. The leftmost lines (which appear rather broad due to defocus) are of Mg and Ca^{+}. Most of the other peaks are identified as Mg, Na, O, H, Si^{+}. There are the many lines of Fe. Towards the right is a very distinctive pattern of lines consisting of atmospheric N and O. The strong line at 7774A is an unresolved triplet of oxygen. Due to the resolution limit, some lines in the blue and blue/green parts of the spectrum may be blended lines from multiple elements including nickel (Ni) chrome (Cr) and aluminium (Al).

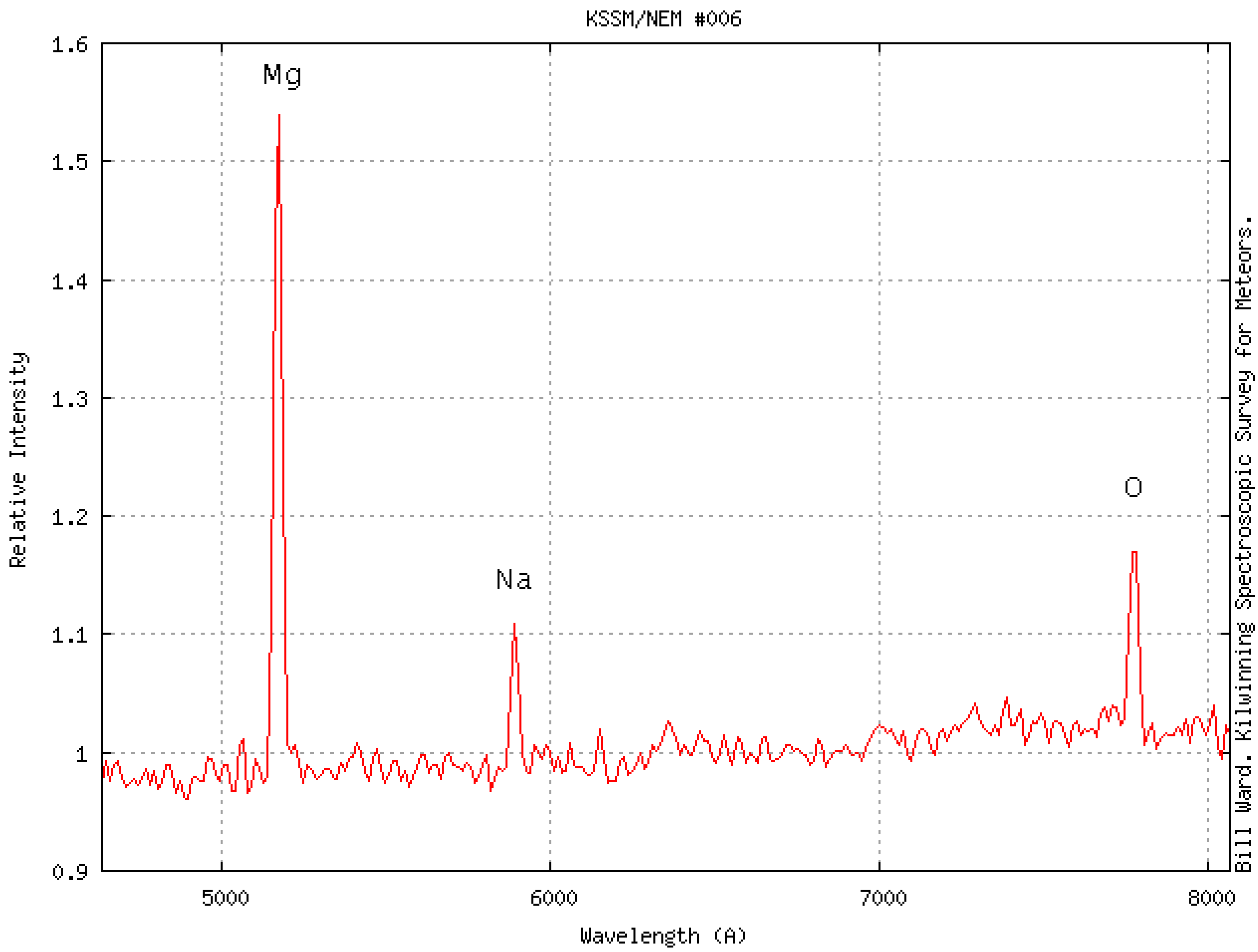


Figure 7. Spectrum Graph KSSM/NEM #006. 20160215_043649UT

Figure 7 notes. This is another "noisy" and weak spectrum. In this case the Mg (5175A) line is much stronger than the Na (5893A) line. The oxygen line at 7774A can also be seen.

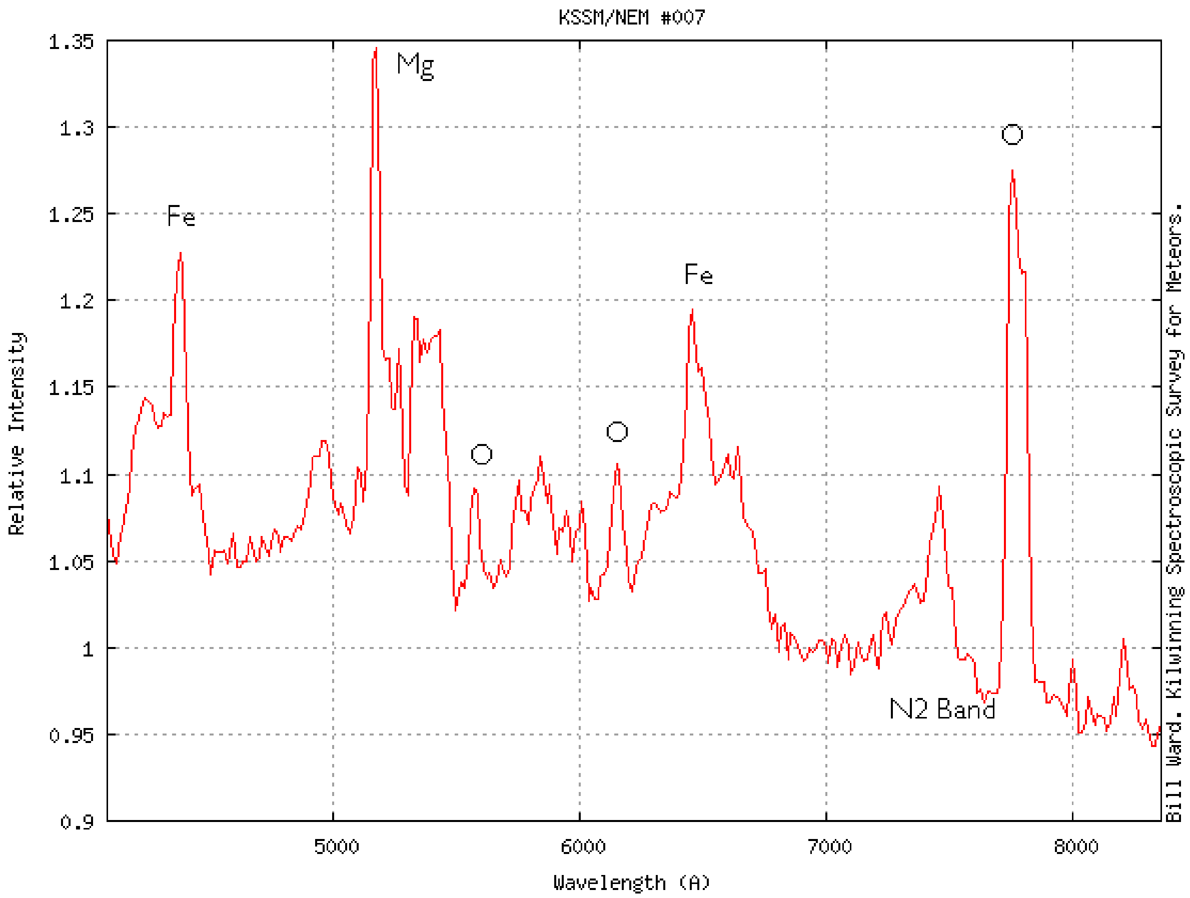


Figure 8. Spectrum Graph KSSM/NEM #007. 20160215_052857UT

Figure 8 notes. In this example many lines of Fe are seen along with a strong Mg line. Some of the Fe lines are particularly strong. What makes this spectrum rather unusual is the absence of the Na line at 5893A. This sodium deficiency is quite noticeable compared to the other spectra in this paper. Emission from O is seen at 5577A and 6156A. The O line at 7774A is also particularly strong. There are also several broad features approximately 6600A and 7450A. These are emissions from atmospheric molecular nitrogen (N_2).

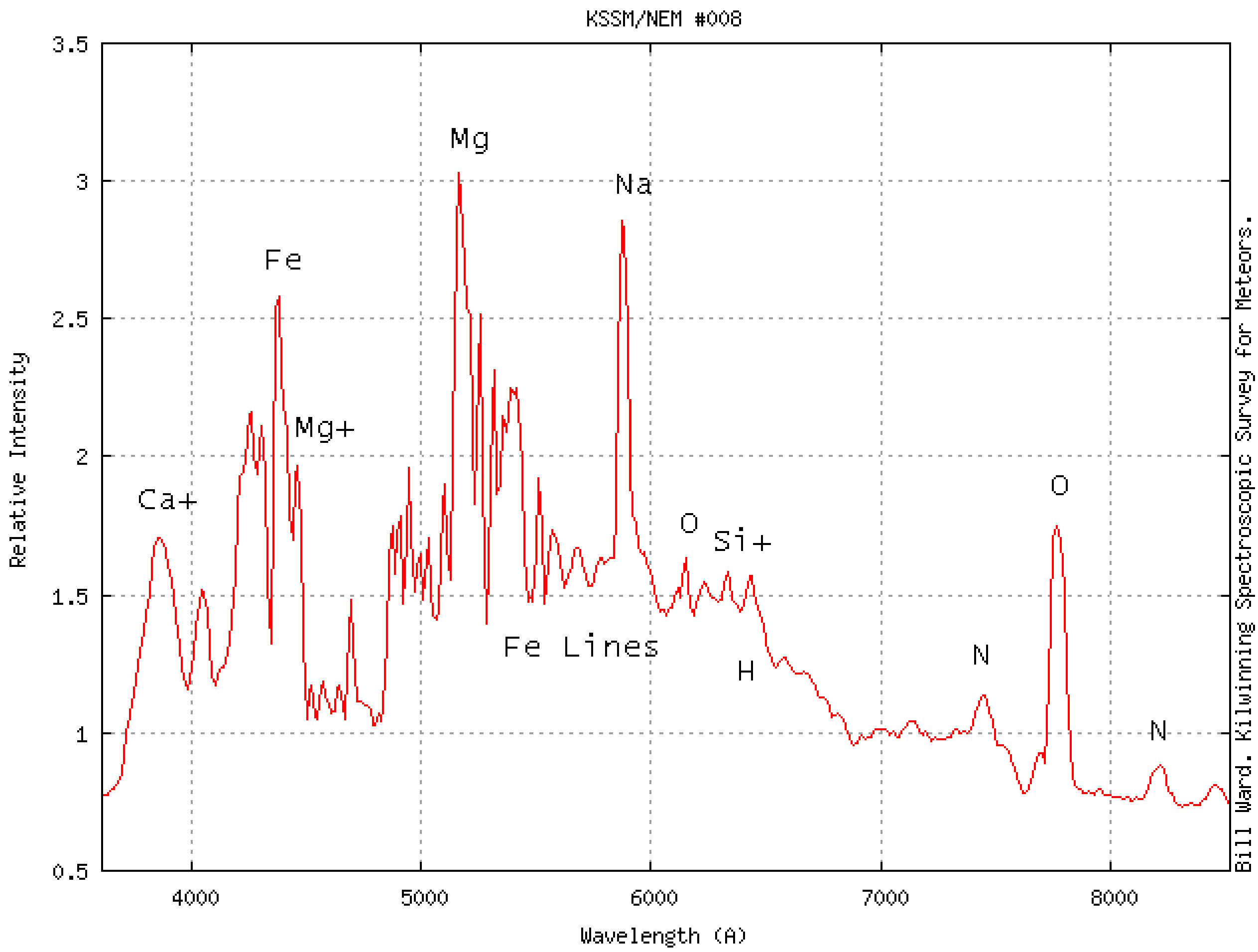


Figure 9. Spectrum Graph KSSM/NEM #008. 20160218_025142UT

Figure 9 notes. Another well detailed spectrum with many features in common with #005. In particular the many Fe lines present. The lines of Mg^+ (4481A) and Mg (5175A) are relatively strong in this spectrum.

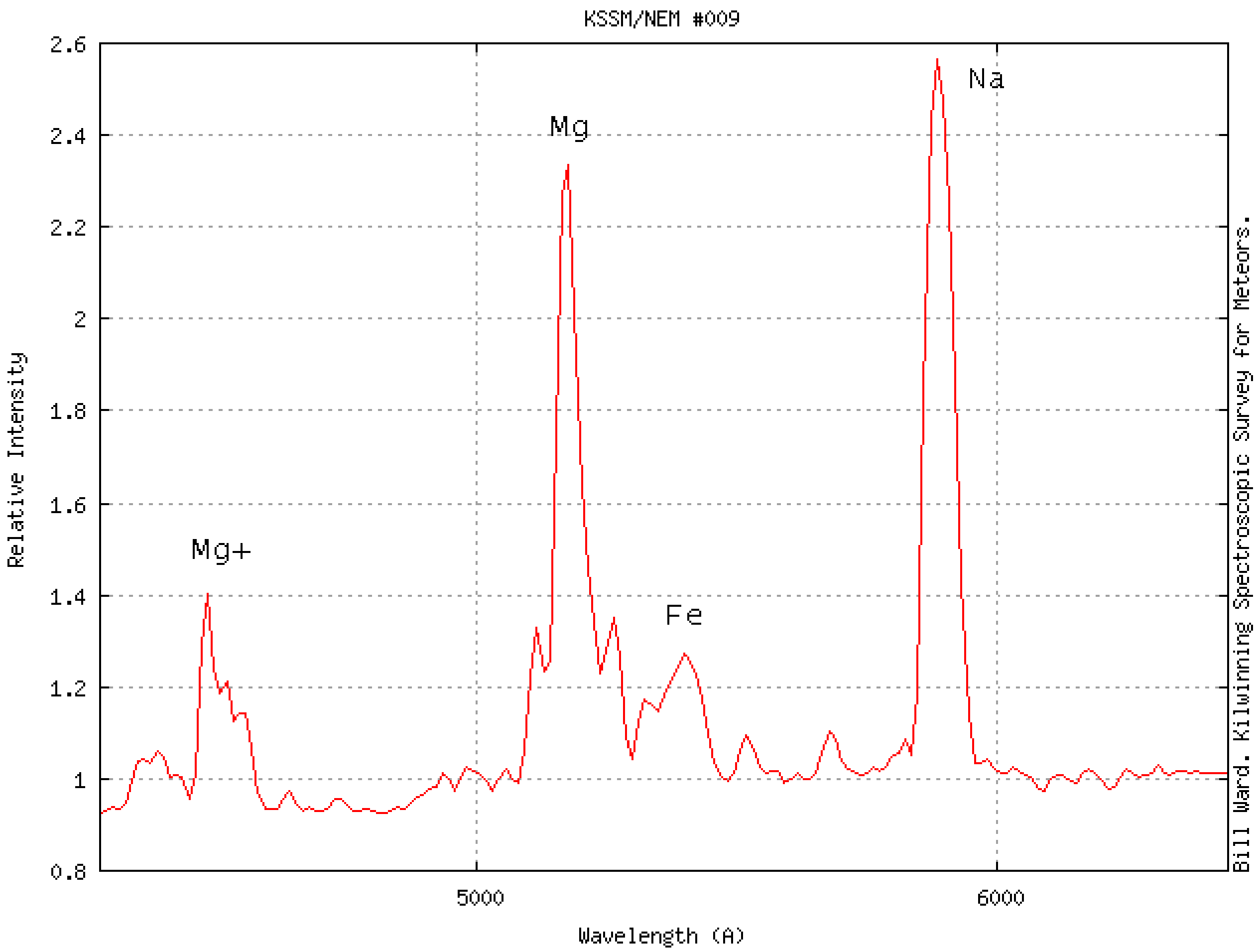


Figure 10. Spectrum Graph KSSM/NEM #009. 20160225_013519UT

Figure 10 notes. This spectrum has the same basic properties as #001. The effective resolution was slightly lower than #001 but the lines of Mg^{+} (4481A), Mg (5713A) and Na (5893A) are prominent. Other weaker lines are from Fe (groups around 4384A and 5328A).

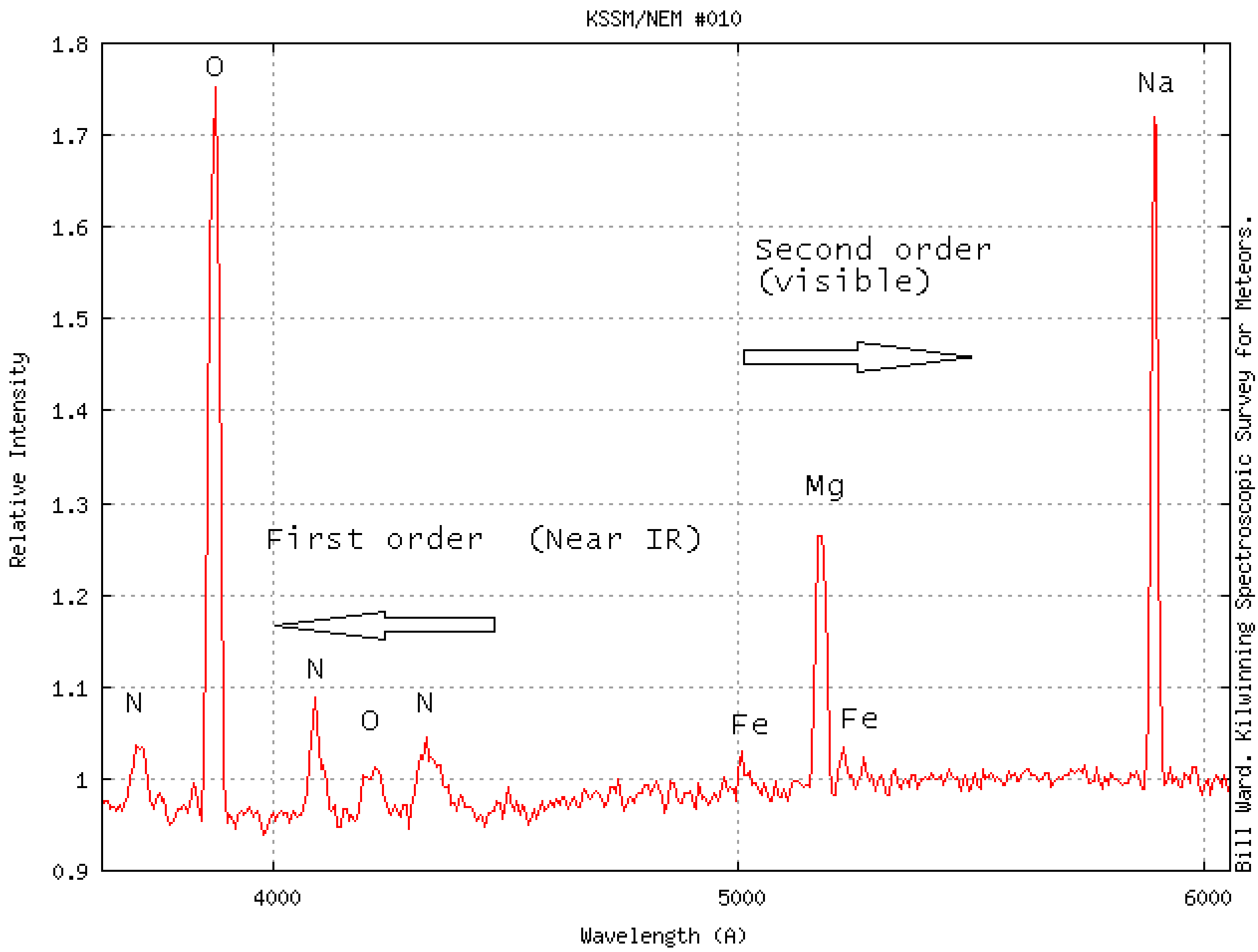


Figure 11. Spectrum Graph KSSM/NEM #010. 20160210_050202UT

Figure 11 notes. This was an unusual spectrum inasmuch that it is slightly misleading due to the plot axis. The five lines centred on 4000A are in reality the N, O (7774A), N, O, N near infrared grouping from the first order overlapping with the second order spectrum. In this spectrum the Mg (5173A) and stronger Na (5893A) lines can be seen along with some weaker Fe lines in the second order.

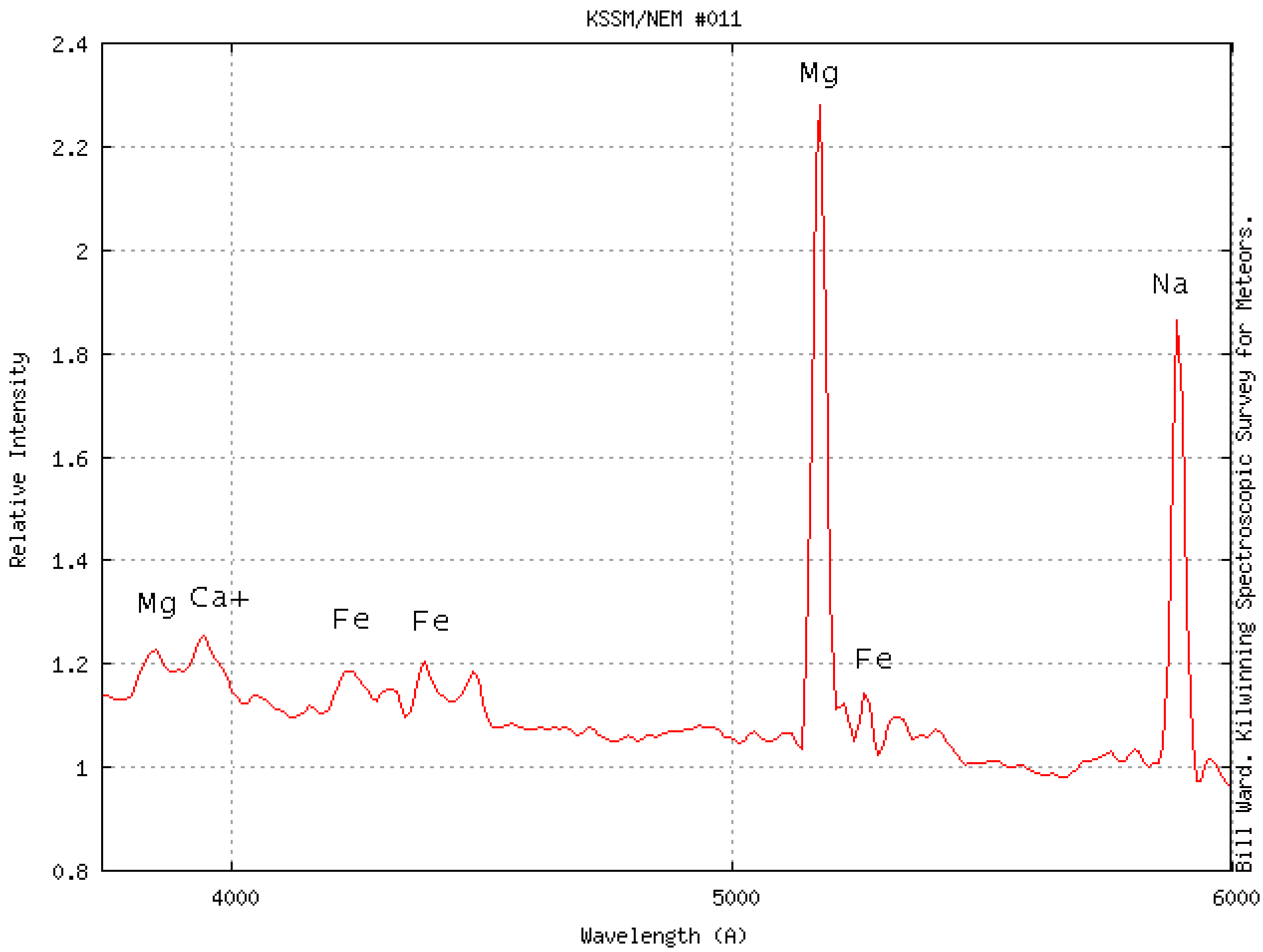


Figure 12. Spectrum Graph KSSM/NEM #011. 20160420_023041UT

Figure 12 notes. Spectrum with strong Mg and Na lines. Weaker Mg (centred 3833A) and Ca^+ (centred 3951A) lines in the near UV are present and several weak Fe lines. Although the actual line intensities are different, there is some similarity between this example and #001, #002, #003 and #009. These have (either) the 5175A Mg line or 5893A Na line as the strongest. The Mg^+ (4481A) and Fe lines being generally weaker.

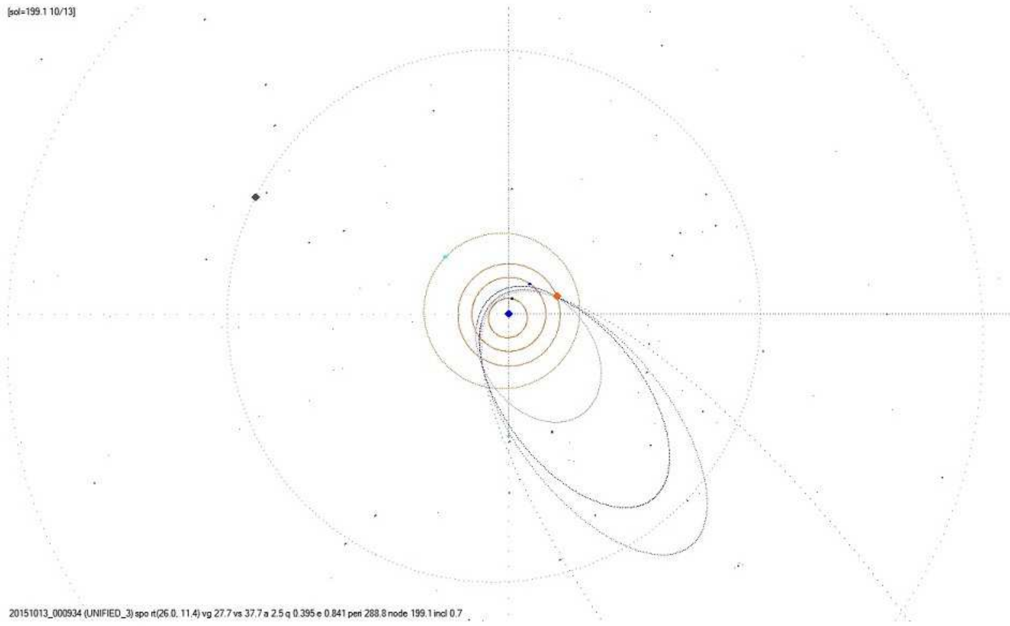


Figure 13. Example orbit.

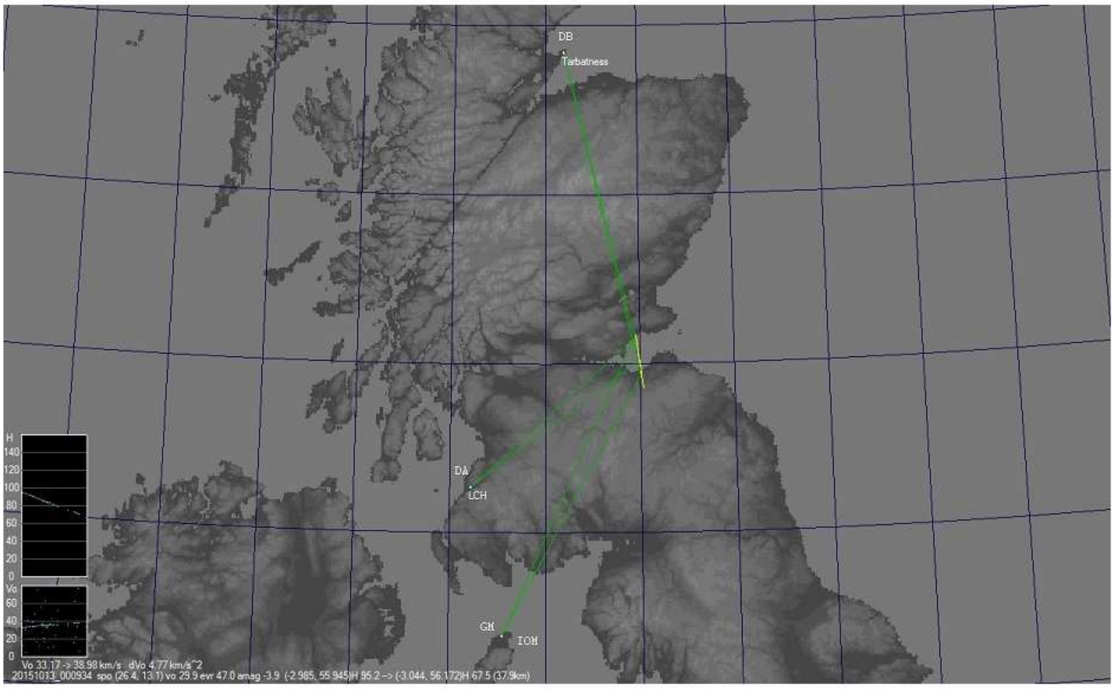


Figure 14. Ground track.

References.

1: NEMETODE Group. http://www.nemetode.org/

2: Asher. D. (2010). International Meteor Conference. Armagh 2010. Short notice request to fill vacant slot from Local Organiser. Private communication.

3: IRIS image processing software. http://www.astrosurf.com/buil/us/iris/iris.htm

4: Visual Spec software. http://www.astrosurf.com/vdesnoux/

5: Ward. B. (2015). Spectro-orbital observation of a sporadic meteor. WGN 43:4. Pp 106-108.

6: Ceplecha. Z. (1968). Meteor Spectra. Survey Paper. IAU. Symposium 33, 73C, 1968. Pp 73-83

7: Rendtel. J. (2002) International Meteor Observers Photographic Handbook. Pg. 47.

8: UFO Capture software suite and manuals. http://sonotaco.com/e_index.html

9: Jewitt. D.(undated) http://www2.ess.ucla.edu/~jewitt/tisserand.html

10: Rudawska. R. (2016). European Space Agency. Private communication.

11: Rendtel. J. (2002) International Meteor Observers Photographic Handbook. Pg. 38.

12: Borovicka. J (2005) Physical and Chemical Properties of Meteors as deduced by observations. IAU Symposium 229, 2005. Pp 249-271.

High altitude wind traced by a persistent train from a Geminid fireball

Bill Ward [1]

Images of a persistent fireball train obtained during observation of the Geminid meteor shower maximum (13/14 December 2012) are used to determine the wind speed at the assumed height of the fireball.

Received 2013 March 28

1 Introduction

There are many images and examples of persistent trains throughout meteor literature. Often mentioned is the fact that the trains are blown and distorted by the winds at high altitude (Rendtel & Arlt, 2009; Bone, 1993).

During observations of the 2012 Geminid meteor shower maximum from Izaña, Tenerife, several bright fireballs were captured using a DSLR camera. Three were observed to have persistent trains. One in particular produced a long lasting persistent train that was imaged over a 11-minute period and which travelled some distance across the sky. Using this train as a tracer a determination of the winds speed at the fireball altitude was made.

2 Observations

The equipment used was a Canon 1000D DSLR camera equipped with a $f = 30$ mm $f/d = 1.4$ lens at $f/1.4$. The camera was set at ISO 800. The lens also had a 500 lpm plastic film grating attached in an attempt to obtain meteor spectra. Exposures in the sequence were 30 seconds each with a 5 second downloading interval between them. Visually the meteor was estimated to be approximately magnitude −6. The fireball is shown in Figure 1.

Figure 1 – Magnitude −6 Geminid fireball (with enlarged section inset), photographed on 2012 December 13/14, at $23^h27^m42^s$ UT.

The train was observed with the naked eye for over 2 minutes.

[1]School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK. E-mail: `william.ward@glasgow.ac.uk`

IMO bibcode WGN-415-ward-wind
NASA-ADS bibcode 2013JIMO...41..160W

3 Analysis

3.1 Determination of train position

The persistent train was recorded in a sequence of 20 images. Using the planetarium software Cartes du Ciel[a] images were superimposed on the stellar fields and the positions of the train determined by simple visual inspection. As the train distorts and fades with time an "exact" position is difficult to obtain with any precision. In this case the determination was made using the leading edge of the train as a guide.

Figure 2 – Image showing start position of train, photographed on 2012 December 13/14, at $23^h28^m18^s$ UT.

Figure 3 – Image showing end position of train, photographed on 2012 December 13/14, at $23^h39^m22^s$ UT.

As this was a single location observation the exact height of the meteor is unknown. A height of 80 km is assumed (Rendtel & Arlt, 2009) and for simplicity the curvature of the Earth is ignored.

The start position was measured as altitude 37.9 degrees (=a in Figure 4), azimuth 73.1 degrees.

The end position was measured as altitude 25.9 degrees (=b in Figure 4), azimuth 45.1 degrees.

[a]Cartes Du Ciel is available free from
`http://www.ap-i.net/skychart/start`

3.2 Determination of distance to train

Using the positions obtained the distance to the start and end points can be determined. As "flat" geometry is being assumed it is straightforward to use the sine identity thus:

$$\frac{80}{\sin 37.9} = \frac{R1}{\sin 90} \quad (1)$$

giving $R1 = 130$ km, and

$$\frac{80}{\sin 25.9} = \frac{R2}{\sin 90} \quad (2)$$

giving $R2 = 183$ km.

With these distances calculated a triangle can now be constructed. The geometry is shown in Figure 4.

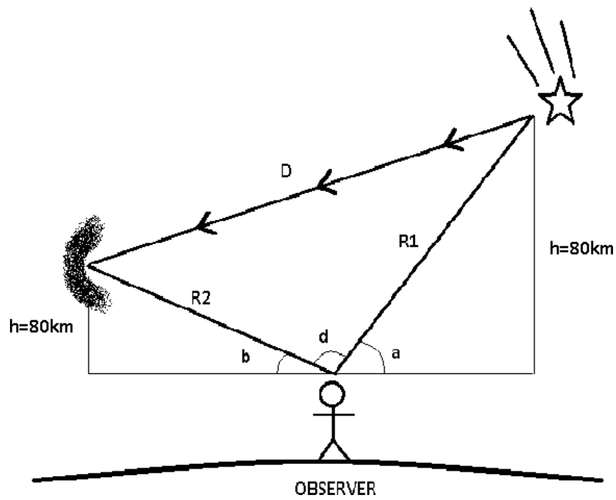


Figure 4 – Geometry of observation. (Foreshortened due to perspective view).

3.3 Distance travelled by train

To find the distance travelled by the train during the interval between the images the cosine identity is used, thus:

$$D = \sqrt{R1^2 + R2^2 - 2\ R1\ R2\ \cos d} \quad (3)$$

Where $d = 73.1 - 45.1 = 28$ degrees, the difference between the two azimuths of position.

Giving $D = 92$ km (= 92 000 m).

3.4 Velocity of wind traced by train

The total interval of time between the first image and last image was 664 seconds. It is now a simple matter to divide the distance travelled by the time taken.

Thus velocity v is

$$v = \frac{92\,000 \text{ m}}{664 \text{ s}} = 139 \text{ m/s} \quad (4)$$

4 Observational errors

4.1 Altitude of fireball

With the altitude of the meteor and train unknown the assumed height, whilst it is felt reasonable, may be in error by a considerable amount. The altitude of fireballs producing persistent trains is quoted as varying between heights of around 110 km to 70 km (Beech, 2006) but in the case of Geminids the average luminous end heights are below 80 km (Betlem et al. 1994b quoted in Rendtel and Arlt, 2009). Therefore 80 km was taken as a representative value. This unknown is in all probability the most significant source of error in this particular calculation. With the variation in possible altitudes it may be in the order of 10 to 20%.

4.2 Train position

The precision of the trains position is ultimately limited by its nature. This is mainly due to it being a feature that is both fading in brightness and evolving in structure over time.

4.3 Geometric approximation

To simplify the calculation a "flat" trajectory is assumed. That is the curvature of the Earth is not taken into account. As such the speed calculated can be considered a lower limit as the curved path would be longer.

5 Conclusion

Using a sequence of images the wind speed at the assumed height of 80 km was determined to be

$$v = 139 \text{ m/s} \pm 20 \text{ m/s}$$

(approximately 499 km/h, or 310 mph).

This is considerably faster than the value of 20 m/s as noted by U. von Zahn (Murad & Williams, 2002) but it comparable to the value of 111 m/s (400 km/h) given as an example by N. Bone (Bone, 1993). This wide range serves to demonstrate the highly variable and dynamic environment that exists in the upper atmosphere.

6 Future work

The observation of several persistent trains from Geminid meteors on the night of 2012 December 13/14 raises a more general issue. It is commonly held that persistent trains are formed only by high velocity meteoroids (Rendtel & Arlt, 2009). However the velocity of the Geminids is relatively slow at 34.6 km/s (Rendtel & Arlt, 2009). Persistent trains from future Geminid showers could be an area for further investigation.

References

Beech M. (2006). *Meteors and Meteorites.* Crowwood Press, UK. (pages 53–54).

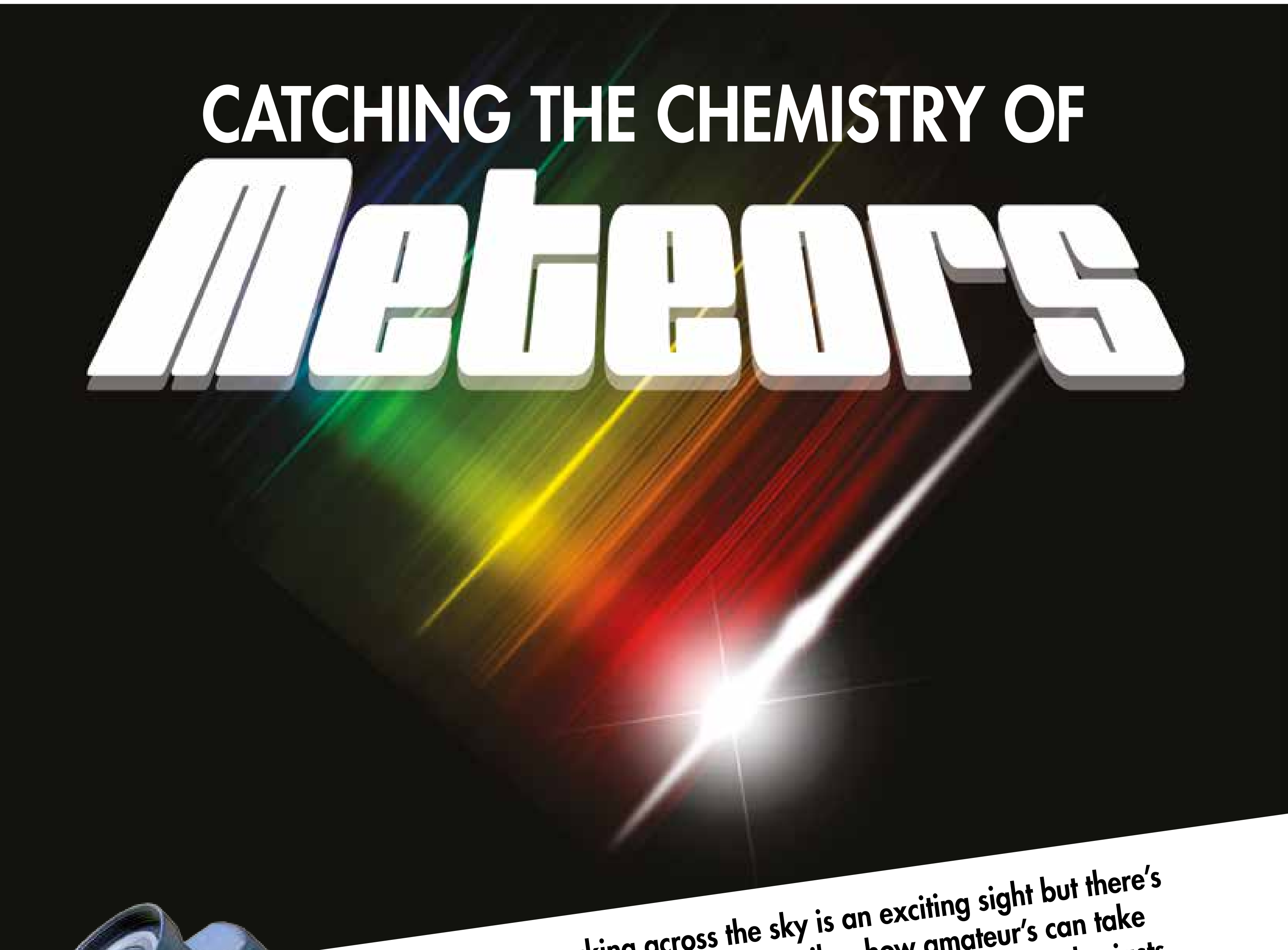
Bone N. (1993). *Observers Handbook Series' Meteors.* George Philip Ltd Publishers, UK. (72–73).

Murad E. and Williams I. P., editors (2002). *Meteors in the Earths Atmosphere.* Cambridge Univeristy Press. (Chapter 7).

Rendtel J. and Arlt A., editors (2009). *Handbook for Meteor Observers.* International Meteor Organisation. (pages 57–58, 95–96, and 170–171).

Handling Editor: Javor Kac
This paper has been typeset from a LaTeX file prepared by the author.

CATCHING THE CHEMISTRY OF Meteors



A shooting star streaking across the sky is an exciting sight but there's science to gained too. Bill Ward **describes how amateur's can take and analyse meteor spectra, joining a dedicated group of enthusiasts already producing valuable results.**

A Watec camera with a 12mm, f/0.8 lens. In front of the lens is a 600 line/mm grating.

Meteor astronomy has undergone something of a revolution in the past few years. The availability of compact, sensitive low-light-level cameras at moderate cost has changed meteor observing almost beyond recognition. Historically, meteor observing was the preserve of dedicated, mostly amateur visual observers, supplemented by photography. Those days have long gone! Video-based techniques have now become the pre-eminent meteor observing method. The changing times were clearly demonstrated at the recent International Meteor Conference, when for the second year running there were no visually based observations presented in any session.

The advantages of video methods are clear. With fast optics they have a comparable limiting magnitude to visual observations. They can be run autonomously, switching on at dusk, tirelessly watching the sky without fatigue until dawn and operating night after night. This technology has led to a large number of new meteor enthusiasts. MILLIONS of meteors have been recorded in the past few years, with many tens of thousands of light-curves being measured and orbits determined.

Video spectroscopy is born

There is now a huge amount of data about 'where' the meteors are coming from, but to enhance our understanding it is desirable to know the meteoroids' composition. Spectroscopy is of course the key astrophysical tool available to astronomers. With it we can determine the elemental composition of any object for which a spectrum can be obtained.

Meteor spectroscopy has been carried out since the 1820s but has often been viewed as somewhat esoteric because of the inherent difficulties. As a consequence relatively few spectra were available to scientists right up until the 1960s. The situation improved as better photographic processes evolved and larger specialist optics became available.

Prior efforts to conduct meteor spectroscopy were mostly done during meteor showers to increase the chances of success. The Leonid meteor storms of the late 1990s produced some remarkable results and gave a glimpse of what could be achieved using the latest CCD and video techniques. The situation now is greatly improved. The quantum efficiency of the modern silicon sensor is vastly superior to film, with also a much broader wavelength sensitivity, from the near ultraviolet at around 380nm to almost 1000nm in the near infrared.

Simply by placing a transmission grating in front of the lens, an ordinary meteor video system can be turned into a power astrophysical tool. This has led to a new field of meteor astronomy being born, called 'Survey Video Meteor Spectroscopy'.

As spectroscopy involves the light being dispersed, the available photons per pixel falls. This results in a poorer magnitude limit than with direct observation. As there are more faint meteors than bright meteors the chances of catching a suitably bright meteor tended to be low in the past.

Multiple capture

With the arrival of the latest high-sensitivity cameras the odds have improved considerably. With fast f/0.8 optics and good-quality gratings, meteors of approximately magnitude +1 can give a useable spectrum. We are now at the point where a suitably equipped station can collect several spectra per night during a shower and one every few nights at other times. There are some unique challenges: even during showers, meteors are essentially random events on the sky. This means an element of good fortune is needed to catch a spectrum. There is even the paradox that in some cases too much light is captured and the spectrum saturates, losing information!

Routine operations to collect many spectra using dedicated systems is now entirely possible. This opens up a whole new world to the amateur who wants to contribute to meteor science. From analysing single events to processing 'big data'; it's all there to be done!

Tools of the trade

The selection of a lens and a grating is a somewhat complex matter. They must balance camera sensor size, field of view, limiting magnitude and practical resolution achievable against the observing time needed to obtain a spectrum. Experience has shown that when using a ½-inch sensor Watec camera, a 12mm focal length lens

RESULTS: IMAGES AND SPECTRA

Once a spectrum has been captured and processed, it is truly exciting what can be seen. Many have the same elements present of course, but it's the subtle differences that catch the eye.

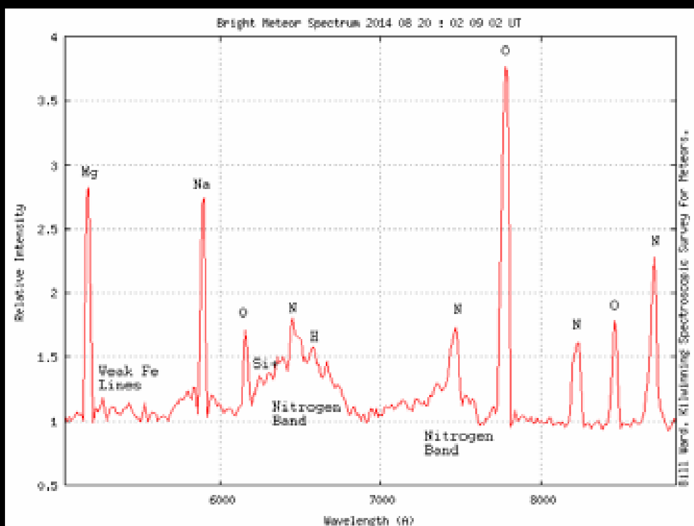
The graphs presented here are of the 'rough outline' type. While they have had basic wavelength calibrations done, they have had no radiometric corrections applied. Although not strictly scientifically valid, this makes the graphs somewhat easier to read. The nanometer (nm) is the SI unit of wavelength, but the angstrom (Å) is still frequently used in spectroscopy. In measurement terms 1nm = 10Å. All of the graphs are calibrated in angstroms, as that is the unit used by the particular software that produced them.

Here are some examples of spectra caught over the past two years or so.

BRIGHT SPORADIC

The meteor itself, a bright sporadic, was not captured in this case. It ran outside the field of view at the bottom of the frame. One of the curious properties of gratings is that owing to diffraction you often don't get to see the actual meteor.

The lines towards the top of the image are caused by the atmospheric gases oxygen and nitrogen. These lines are very useful in determining the direction of increasing/decreasing wavelength in the spectrum. They are also a useful starting point for wavelength calibration.



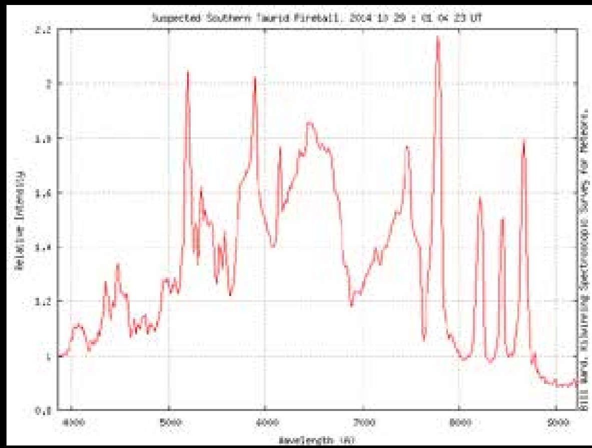
This is a nicely detailed spectrum and is typical of what can be achieved with a 12mm lens and a 600 line/mm grating. The measured dispersion is approximately 1.2nm/pixel (12Å/pixel). This is not the same as the resolution. The effective resolution is the smallest feature that can be fully discerned from its neighbours. In this case it is around 3nm (30Å). It is a good example to start with as it has many features and lines common to many spectra. Prominent lines include neutral magnesium (Mg) at 5175Å, sodium (Na) at 5893A and a very prominent oxygen (O) line at 7774Å. Others include iron, hydrogen, nitrogen, silicon and calcium. This may have been a late Perseid meteor.

Bright fireballs

The image below shows what may have been a Southern Taurid fireball. The spectrum graph spans almost the entire range of wavelengths detectable by a silicon-based sensor and is nicely detailed.

The spectrum of the fireball shows many lines, including those of magnesium, sodium, silicon, calcium, nickel, chromium, oxygen and nitrogen, plus many iron lines.

A suspected 2014 Southern Taurid Fireball.

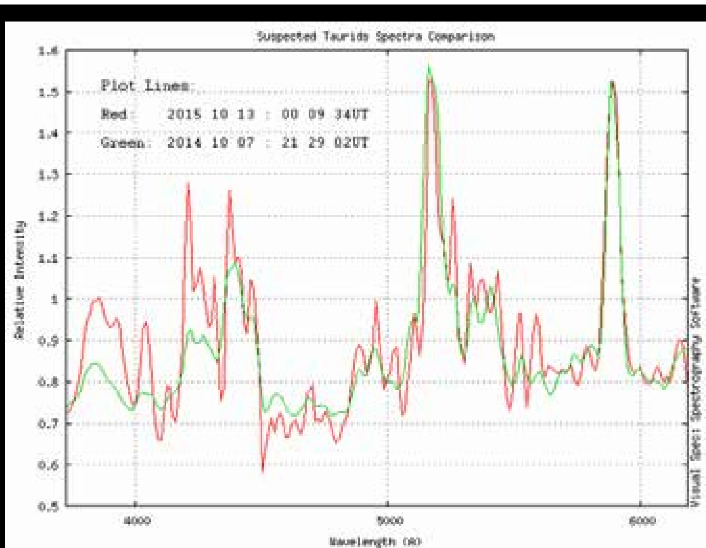


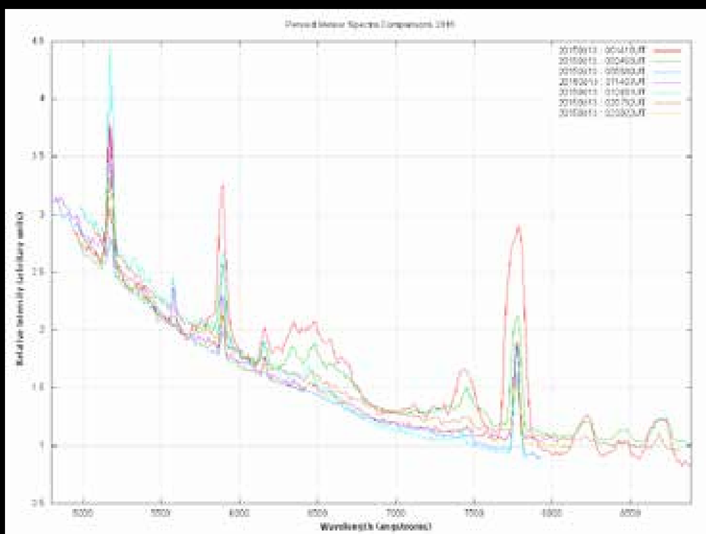
COMPARATIVE SPECTROSCOPY

An intriguing use of meteor spectra is to compare various spectra from the same source. This 'comparative spectroscopy' may be a useful tool.

The spectra of two suspected Southern Taurids are shown here. It is immediately clear that they have a very similar composition. Despite the variation in intensities, the vast majority of the lines map well from one spectrum to the other. If similar spectra are obtained from confirmed Southern Taurids, this would give confidence that these were indeed from that stream. It would be impossible to tell this with any other observing method. Only spectroscopy has the power to do this.

It is also interesting to compare spectra obtained from the same shower to each other. In the bottom image there are seven spectra obtained from Perseid fireballs during the peak of the shower in 2015. The individual spectra used here have had a flux correction applied to correct for the wavelength sensitivity variations of the sensor. Examination shows that again there are slight differences in line intensity. However, it can be seen that all the individual spectra show the same basic characteristics , thus identifying them as coming from the same source. Although not instrument corrected, the spectrum on page XX has many of the same features – look between 6000A and 7000A. This does suggest that the bright sporadic was indeed from a late Perseid.





SOFTWARE SOURCES

1. UFO Capture software: details at SonotaCo.com/e_index.html
2. IRIS image processing software: details at astrosurf.com/buil/us/iris/iris.htm
3. Visual Spec spectroscopy analysis software: details at astrosurf.com/vdesnoux/

and a 600 line/mm grating is a reasonable choice.

It is interesting to note that commercially available CCTV cameras such as the latest Watec cameras are so good that they are also being used by professional researchers. This means that, in terms of hardware, the amateur is now almost exactly on a par with professional scientists!

The actual spectra are imaged using the appropriate software and video-grabbing hardware on a PC. Most observers use the UFO capture suite for this. Once obtained, the image must be turned into a useful graph. There are several free or commercial packages that can be used. For the examples in this article, the free IRIS and Visual Spec software were used. See Software sources box on p. XX for details of these software programs.

The spectrum graph

It may appear as a graceful streak of light in the night sky, but the meteor process is rapid and violent. On entering Earth's atmosphere, the meteoroid is subject to both extremely rapid deceleration and temperature rises, essentially going from, say, 40 km/sec to zero and from the temperature of space to around 4000 degrees in approximately a second! In this brief time the meteoroid is basically turned into glowing atoms and the high temperatures causes the individual atoms to become excited. It is this excitation that leads to the emission of light. Each element has its own unique 'fingerprint' of light. Measuring this fingerprint is the key to analysing the light and determining which elements are present in the meteor.

Spectrum plots are simply graphs of the light intensity versus wavelength. Producing an actual spectrum is done through preprocessing the original image and then analysing it to arrive at the final spectrum plot. The ease with which the processing can be done on computers means that any given spectra can be reprocessed as many times as one wishes, depending on the observer's own goals, from rough outline to full radiometric correction.

Line identification and 'fitting' is challenging. With video systems, the limiting factor is the resolution achieved, and this will vary from spectrum to spectrum on the same system, depending of the observing geometry.

Multiple closely spaced lines can appear as single lines if the resolution is insufficient to separate them, as in the case of the magnesium 'line' at 5175A. This is actually a triplet of three magnesium lines at 5167A, 5173A and 5185A. This is of course also a problem with closely spaced lines of different; what element are you actually seeing? Comprehensive listings of spectral lines are available. A basic listing is included in Visual Spec and these can help, but often it cannot be said with certainty which line is which.

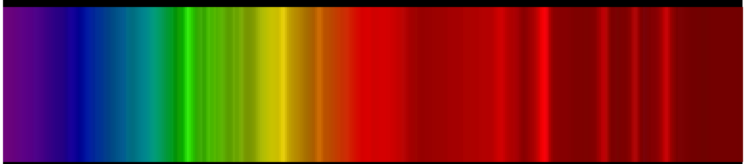
There are yet more difficulties with molecules. Most molecules disassociate during ablation, but not all. Those left tend to produce a huge number of very closely spaced lines, leading to very broad humps in low-resolution spectra. In Figure 2 the broad features ('bands') around 6500Å and 7400Å are due to atmospheric nitrogen molecules.

Bill Ward is an active member of the SPA's Meteor section and the NEMETODE group.

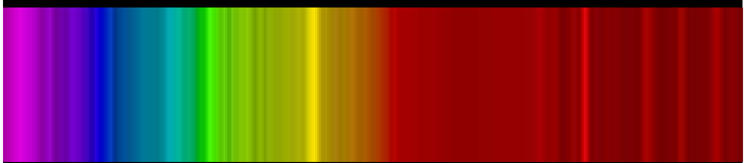
SYNTHETIC SPECTRA

It is often said that a picture is worth a thousand words. This is true of many astronomical images. Although necessary for proper analysis and understanding, the graphs can look just a little dull to the untrained eye. But with a little digital wizardry, a more colourful view can be had.

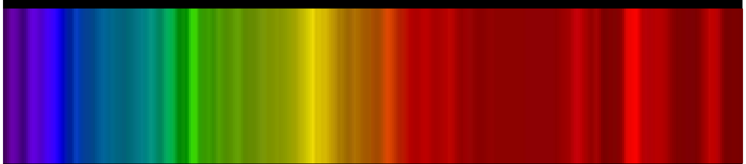
Since meteor spectra are caused by glowing atoms they produce what are called emission spectra. By remapping the graphs , colourful 'synthetic' spectra can be made. These can produce beautiful and dramatic images. However, it should be remembered that wavelength coloration is false. The colour range has been stretched to make the ultraviolet and infrared lines (where captured) visible.



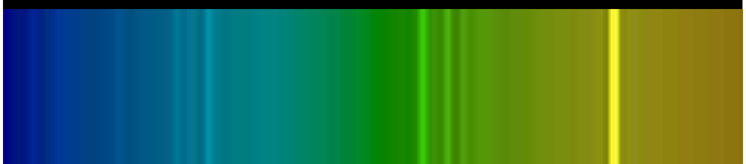
Colour synthetic emission spectra of the bright sporadic (top) possible Perseid meteor, and a possible Southern Taurid fireball (see page XX).



A suspected Southern Taurid, from 2015.

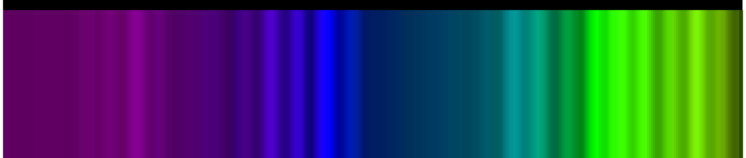


A fireball captured at 04h 50m 59s UT on 28 December 2014.



A bright meteor captured at 00h 55m 21s UT on 23 April 2015. This spectrum was captured using an 830 grooves/mm grating, so it has a slightly higher resolution than the previous examples.

A bright meteor from 04 37 43 UT on 8 January 2016, captured through an 830 groves/mm grating at almost optimal dispersion showing very sharp lines.



The distinctive spectrum of an iron meteor (unfortunately at rather low resolution).

High-altitude wind traced by persistent train from Geminid fireball

William Ward

School of Engineering, University of Glasgow, Glasgow, G12 8LT, United Kingdom
`william.ward@glasgow.ac.uk`

Images of a persistent fireball train obtained during observation of the Geminid meteor shower maximum (December 13/14, 2012) are used to determine the wind speed at the assumed height of the fireball. The images were taken using ordinary consumer grade photographic equipment and analyzed to determine the relative positions of the persistent train over an interval of time. The positional data were then used to determine the wind speed using simple plane geometry and an assumption of the fireball altitude based on past determinations. The speed of the wind was determined to be 139 m/s.

References

Ward W. (2013). "High altitude wind traced by a persistent train from a Geminid fireball". *WGN, Journal of the IMO*, **41**, 160–161.

During the Friday morning coffee break, we see Nagatoshi Nogami talking to Casper ter Kuile and Bill Ward to Paul Sutherland. (Credit Axel Haas.)

Video meteor spectroscopy

Bill Ward

William.ward@glasgow.ac.uk

Observational examples produced by the Kilwinning Spectroscopic Survey for Meteors are presented.

1 Introduction

The poster presented at the 2015 International Meteor Conference held in Mistelbach, Austria, illustrated some of the spectra obtained in the past year as part of the Kilwinning Spectroscopic Survey for Meteors.

2 Equipment

A variety of Watec cctv cameras are used at the observing station. The three primary cameras used for spectroscopy are two Watec 902H2 Ultimate and a Watec 910HX/RC.

These are fitted with 12mm f0.8 lenses carrying 600 groove/mm gratings.

Additional cameras are also used for general observing and determining out of field meteors as captured by the spectroscopy cameras. These are a Watec 902H2U and a Watec 910HX/RC.

3 Results

Operational Time

From April 2014 to April 2015 the cameras observed for a total of 714 hours. In this time 105 spectra were captured. Most of these were partial spectra, that is, some of the spectrum fell outside the field of view of the camera. However several complete and interesting spectra were obtained.

Examples

Figures 1 to 4 show some examples of complete images and spectra captured during the year.

Figure 1 – Sporadic Fireball #1.

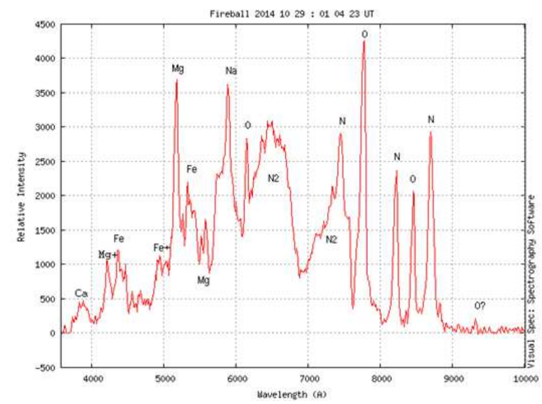


Figure 2 – Sporadic Fireball #1 Spectrum.

Figure 3 – Sporadic Fireball #2.

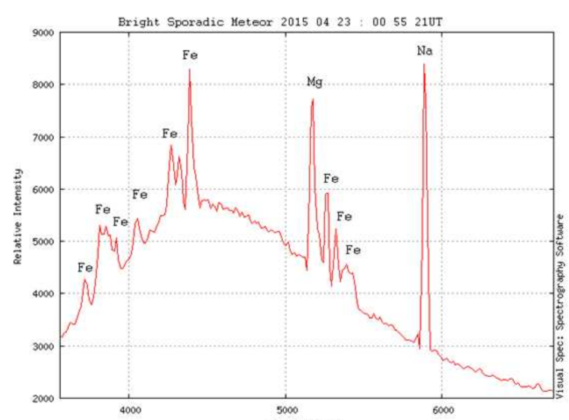


Figure 4 – Sporadic Fireball #2 Spectrum.

4 Dual station observations

Working with David Anderson of the Network for Meteor Triangulation and Orbit Determination

(NEMETODE)[1] dual station observations were conducted. This resulted in the capture of a bright fireball on the night of 10 April 2015 at $00^h58^m38^s$ UT. Analysis revealed an aphelion from with the asteroid belt and several bright emission lines from Magnesium, Sodium and Iron. This is illustrated in *Figures 5 and 6*.

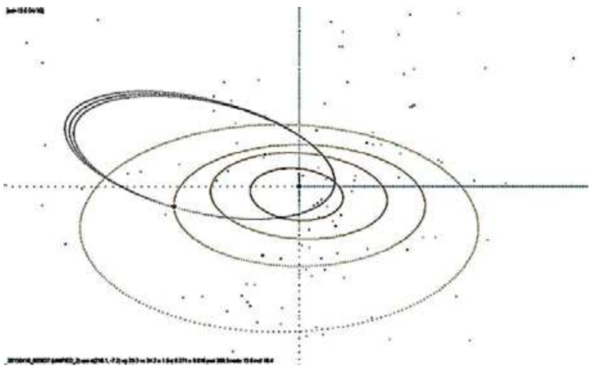


Figure 5 – 3D perspective orbit of dual station capture.

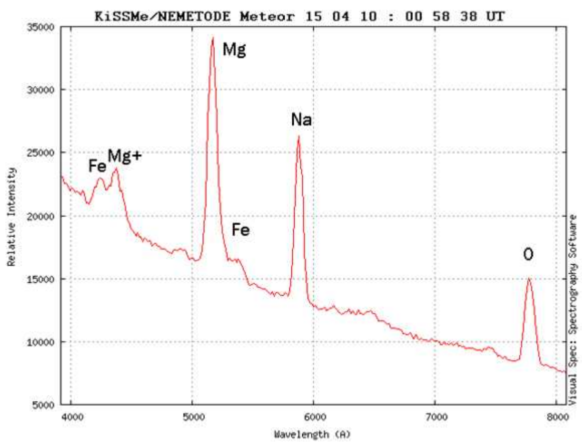


Figure 6 – Spectrum of dual station meteor.

5 Conclusion

The Kilwinning Spectroscopic Survey for Meteors produced 105 spectrums over the course of one year of operation with 714 hours of actual observational time.

Dual station observations were made in cooperation with David Anderson (Low Craighead Farm, Ayrshire) of the NEMETODE Group. These observations allowed the orbital and spectrum characteristics of a meteor to be determined. This is the first time that such an observation has been made from Scotland (UK).

Acknowledgment

The author would like to acknowledge the cooperation of, David Anderson of Low Craighead Farm, Ayrshire for his work in capturing the dual station meteor.

[1] NEMETODE Group. http://www.nemetode.org