ONE HUNDRED AND FIFTEEN YEARS OF METEOR SPECTROSCOPY

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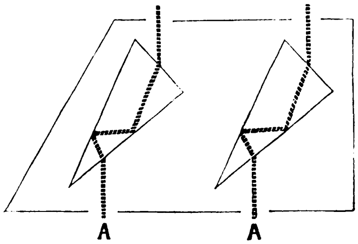
Abstract. Early visual observations of meteor spectra were instigated by A.S. Herschel and, in the period 1866-1880, resulted in the recording of several hundred spectra and the correct identification of the lines of neutral sodium and magnesium. Some 60 meteor spectra were photographed from 1897 to 1940, which resulted in the identification of 9 neutral and 4 singly ionized atoms. Improved cameras and techniques after World War II, and in particular the use of closed-circuit television equipment recording on video tape, increased the data-bank of meteor spectra to several thousand and made possible the identification in these spectra of between 15 and 20 neutral atoms, 9 singly ionized atoms and 6 diatomic molecules. Reliable luminous efficiencies of the atoms and molecules radiating in the observed light of meteors are available in only a few cases. Where relative abundances of the elements have been calculated, these agree in general with those found by other techniques for interplanetary dust, and with abundances for the solar system as a whole.

INTRODUCTION

Meteor spectroscopy is a small field in experimental astrophysics but it has the unique feature of telling something about the chemistry of specific cometary fragments in the 10^{-1} to 10^3 g mass range, while, for shower meteors, each fragment can be positively identified as originating in some comet. The chief observational difficulties in this field of research are the very brief duration of the average meteor and the highly random nature of both the time of appearance and the position in the sky of each visible meteor. The only departure from complete randomness in these observational parameters is the fact that the average frequency of meteors varies with time according to rules determined by previous observations. For example, at certain periods in the year the earth passes near the orbits of specific periodic comets, and fragments from these comets appear in our atmosphere as meteors which normally increase in frequency to peaks on given dates (Cook 1973).

I. Halliday and B. A. McIntosh (eds.), Solid Particles in the Solar System, 121–128.



THE HERSCHEL-BROWNING METEOR SPECTROSCOPE.

Fig. 1. From the Intellectual Observer 10, p. 38, 1866.

VISUAL OBSERVATIONS

The pioneer in meteor spectroscopy was Prof. Alexander Stewart Herschel (1836-1907), second son of Sir John Herschel and grandson of Sir William Herschel, the discoverer of the planet Uranus in 1781. In 1863 Alexander Herschel designed a direct-vision, binocular, visual meteor spectroscope (Figure 1) which was constructed by the optician John Browning. The angle θ of each prism, nearest the entrance pupil A, is defined by $\sin 2\theta = 1-1/\mu^2$, where μ is the index of refraction of the glass used for the prisms. The field of view of this spectroscope was approximately 20° in diameter and the first meteor spectrum recorded by Herschel was observed on 18 January, 1864 (Herschel 1865). A number of these meteor spectroscopes were ordered by the British Association for the Advancement of Science and Herschel distributed them to various persons interested in the observation of the Leonid meteors, which were expected to return with a strong shower in November, 1866.

In the period 1866-1880 some 300 to 400 meteor spectra were recorded visually by Herschel, Browning, Nicolaus von Konkoly, A.P.A. Secchi and others; see bibliography by Millman (1932). As early as 1866 Herschel (1866) had correctly identified the D lines of sodium in emission as a frequent and prominent feature of Perseid spectra, often present against a background that appeared continuous. In the 15-year period noted above both sodium and the green triplet of magnesium were listed as statistically prominent in the majority of meteors, while among less positive identifications it was suggested that many of the numerous lines seen in the blue-violet could be due to iron. Both sodium and magnesium were also identified in enduring meteor trains that lasted, in some cases, upwards of 10 minutes. Since at this time in the 19th century spectroscopists were very familiar with the visual appearance of line spectra, we must give their identifications more weight than we would to visual observations made today, when practically all spectroscopists use instrumental recording.

EARLY PHOTOGRAPHIC SPECTRA

A photographic spectrum consisting of only 6 features appeared by chance on a Harvard objective-prism plate in 1897 (Pickering 1897) but the first meteor spectrum secured on a program for meteor photography was obtained by S. Blajko at the Moscow Observatory on 12 August, 1904, at the peak of the Perseid meteor shower. Blajko photographed a total of three meteor spectra and in one of these correctly identified in the blue-violet neutral and ionized calcium and neutral magnesium (Blajko 1907). There seems to have been no further effort to photograph meteor spectra until the early thirties, though a few were obtained by chance on programs of stellar spectrography (Millman 1932).

In 1931 the writer conducted a brief program of meteor spectrography (Millman 1932) and in 1932/33 a systematic program where three spectrographs were exposed on all clear, dark nights over a period of 12 months, supplemented by additional instruments used during major meteor showers. These observations resulted in the photography of 13 additional meteor spectra (Millman 1935). During the thirties interest in this field developed slowly, primarily in Canada, the USA and the USSR. The meteor observers involved included a number of experienced amateur astronomers. Advances in available photographic emulsions and improvements in the cameras used both contributed to new results. Ortho plates, sensitive in the yellow-green, were already available for the 1932/33 program, and fast panchromatic plates, recording down into the red wavelengths, were used in 1933/34 (Millman 1934). In 1936 a rotating shutter, occulting the lens several times per second, was used on meteor spectrographs (Millman 1936,1937). This device not only records the apparent angular speed of the meteor across the field of view but makes possible the separation of the trailing luminosity, wake or train, from the primary meteor image, termed the head. By the end of 1940 a total of 60 meteor spectra had been recorded photographically (Millman 1952), when World War II intervened. Low-excitation lines of the atoms listed in Table 1 had been reliably identified in these spectra.

Table 1

Na I, Mg I, Al I, Si I, Ca I, Cr I, Mn I, Fe I, Ni I, Mg II, Si II, Ca II, Fe II.

POST-WAR PROGRAMS

The termination of the War was marked by an outstanding meteoritic event, the strong meteor shower on October 9/10, 1946, produced by a relatively dense swarm of meteoroids moving in the orbit of the periodic comet Giacobini-Zinner, 1946 V. More than 20 spectra of these slow meteors, velocity in the atmosphere 23 km/s, were photographed in Canada (Sky Telesc. 7, p. 136, 1948). These spectra exhibited no lines of ionized atoms but only Na I, Mg I, Ca I, Mn I, Fe I, and the first positive bands of N_2 (Millman 1972).

After World War II interest in the observation of meteors spread rapidly as war-surplus radar equipment and aerial cameras were converted for use in meteoritical research. In 1950 good replica transmission gratings became available and these largely displaced objective prisms as the dispersing units in meteor spectrographs (Millman 1956). Also in 1950 a fast infrared emulsion became available for use in aerial cameras and extended the photographic coverage of meteor spectra to approximately 9000 Å (Millman 1953). Using a specially designed UV lens Halliday (1969) extended the identification of lines in meteor spectra to 3100 Å in the ultraviolet. Spectrographs with dispersions considerably better than 100 Å/mm were used at a number of observing centres, and with particular success at the Ondrejov Observatory in Czechoslovakia (Ceplecha 1971), where in one case over 1000 separate features were measured in a single spectrum.

Later, two important instrumental advances resulted in the recording of the spectra of fainter meteors than had been possible previously. Harvey (1973,1974) employed a battery of fast Maksutov cameras, aperture ratios f/1.0 and f/1.3, in a systematic program of meteor spectrography carried out in New Mexico, USA; and Hemenway pioneered in the use of electronic image intensification (Hemenway et al. 1971) by recording meteor spectra on video tape with image-orthicon equipment at the Dudley Observatory, Albany, NY, USA.

The forbidden line of O I at 5577 Å was first identified in meteor spectra by Halliday (1958), a line which exhibits a duration of several seconds in the case of bright, fast meteors. A detailed study of the spectra of meteor wakes and meteor trains was made possible by the development of the jumping-film camera (Halliday and Griffin 1963). The decay characteristics of the 5577 Å oxygen line were studied, using the jumping-film camera (Gault 1970) and the video-tape records obtained with the image orthicon (Millman et al. 1971). An image-intensification system still more sensitive than the image orthicon was first used for meteor spectrography by Clifton in 1972 (Clifton et al. 1979). This system has the added advantage that spectra can be recorded into the near infrared. During the Geminid meteor shower in December 1974 the spectra of 1300 meteors were recorded in four nights with this low-light-level television system, which includes an S-20 photocathode coupled to a Secondary Electron Conduction (SEC) vidicon tube (Clifton et al. 1979). These data are now being analysed photometrically with the help of the Image Data Processing System (IDAPS) at the Marshall Space Flight Center, Huntsville, AL, USA (Millman and Clifton 1979). Using a somewhat different equipment, which includes a Silicon Intensified Target (SIT) vidicon tube, meteor spectra were recorded from a high-flying Lear Jet aircraft and successfully combined with high-power radar echoes recorded at a ground station near Ottawa, ON, Canada during the Quadrantid meteor shower in January 1976 (Millman 1976).

In the USSR television techniques have also been used in recording meteor spectra, commencing in 1972 at Ashkhabad in the Turkmen SSR (Anisimov et al. 1976; Mukhamednazarov and Smirnov 1977; Mukhamednazarov 1977). The system employed included a superorthicon, and the N_2^+ molecule was identified as an enduring feature in the spectra of faint meteors.

The results of the observational activities noted above, plus a number of other programs carried out by both professional and amateur astronomers, has been the accumulation of between 3000 and 4000 meteor spectra instrumentally recorded. Atoms and molecules identified, in addition to those listed in Table 1, are given in Table 2. In general the light radiation observed from meteors results from low-excitation (average 5 to 6 eV) atomic line radiation, plus the bands of some well-known diatomic molecules (Millman 1968). A unique feature is the strong enhancement of the lines arising from intersystem transitions, in particular those by transitions to the ground state of the atom. Good examples are the lines of Mg I at 4571 Å and Ca I at 6573 Å. Of the 17 most abundant elements in the solar system, by weight (Cameron 1973), all but sulfur and the inert gases have been identified in meteor spectra. Where reliable laboratory values for luminous efficiencies are available for atoms radiating under conditions of collisional excitation in the upper atmosphere (Savage and Boitnott 1973), the relative abundances of the elements determined from meteor spectra seem to agree with Cameron's values (1973) for the solar system as a whole (Millman 1979).

Table 2

H I, N I, O I, Ti I, Co I, N II, O II, Ti II, Cr II, Sr II, N_2, CN, FeO, C_2, N_2^+; possibly also C I, Sr I, Ba I, CH.

THEORETICAL RESEARCH

This survey has been concerned primarily with the observational aspects of meteor spectroscopy, but a brief note is added here on the theoretical work that has related particularly to this field. Much is owed to the early concepts of Öpik (1958). A.F. Cook (1955,1968) was also an early contributor to the theory. Ceplecha (1964) employed the emission curve of growth of Fe I in a theoretical study of a bright meteor flare and later (Ceplecha 1973) developed a general model of spectral radiation for bright fireballs. Rajchl (1974) discussed the effects of various physical parameters on the general characteristics of meteor spectra. In recent years by far the most prolific contributor to the theory of meteor spectra, including the spectra of wakes and persistent trains, has been W.J. Baggaley. For example, he has discussed the production of the 5577 Å line of O I (Baggaley 1976), the role of ion neutralization in wake luminosity (Baggaley 1977a), the O_2 molecule as the origin of the red glow of long-duration trains (Baggaley 1977b), and a sodium catalytic cycle which can produce persistent trains with durations longer than one hour (Baggaley and Cummack 1979).

CONCLUSION

In the future, activity in meteor spectroscopy should concentrate, where possible, on the photometric analysis of a well-considered selection of the meteor spectra already recorded, and the application of these data to the larger problems of cometary origin and evolution. Further laboratory research on the luminosities of atoms and molecules under conditions of collisional excitation is essential. The results of ground-based programs involving the observation of asteroids, comets and meteors should be combined with results secured by spacecraft, to improve our knowledge of the complex of small solid particles in the interplanetary space of our solar system.

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DISCUSSION

Roach: Are the elemental abundances given with respect to the meteor or to the atmosphere?
Millman: The relative abundances listed from observations of meteor spectra refer to those elements that originate primarily in the meteoroid. Oxygen is common in both meteoroids and the atmosphere and it is impossible to estimate the percentages coming from each source. Nitrogen is likely relatively rare in meteoroids and almost all of this element recorded in meteor spectra must originate in the atmosphere.

Lokanadham: Is the presence of sodium in meteor spectra correlated with the sodium line presence in airglow spectra?
Millman: At present no photometric data are available on this point. Since the sodium line appears in the great majority of meteor spectra it is doubtful that there is any strong correlation with the airglow.

Lokanadham: Does the composition of meteoroids contribute to the evolution of some meteor streams?
Millman: The physical properties of the meteoroids in any given stream must contribute to its evolution as the less dense and more friable

meteoroids will be subject to a more rapid fragmentation. The chemical composition will also have an effect since meteoroids with large percentages of the light volatile elements will tend to break up more easily than those consisting primarily of the heavier elements.