Radio Observations of Meteors

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It is a well-known fact that, when a meteoroid enters the earth's atmosphere at high velocity, a portion of the kinetic energy is expended in creating large numbers of ions along the path of the meteor. The long thin column of ions rapidly expands and diffuses and is distorted by the winds of the ionosphere until it eventually disappears. This meteoric ionization may serve as a radio target, and it thus makes possible a new method of studying both the astronomical properties of meteors and the physical conditions in our upper atmosphere.

At the close of World War II, a considerable quantity of powerful radio equipment was available for fundamental scientific research, and this fact was largely instrumental in promoting studies in radio astronomy. The serious application of radio methods in meteoric astronomy may be dated from the great Giacobinid meteor shower of October 1946. The radio results obtained on this occasion were so conclusive that world-wide interest was aroused in the potentialities of radio techniques, and these have now become an important division of the research in this field.

It is not the purpose of this paper (*1*) to deal with the history of this development, nor does it describe in any detail the various, and often ingenious, types of equipment devised by the radio engineers. The theoretical treatment of meteoric ionization and its effect on the ionosphere is a subject that, at the moment, is being actively pursued by a number of investigators, but it is too early to give a satisfactory survey of the basic theoretical conclusions. Rather, this paper is a brief summary of the most significant observational results secured through radio studies of meteors during the last 7 years. The origin of the results is indicated by references to some of the representative papers.

Although research publications dealing with this subject have appeared in approximately ten countries, the major effort has been restricted to three—England, the United States, and Canada. Observers have, in general, used wavelengths in the 1- to 100-m range, with either pulsed or continuous wave transmission on powers up to 400 kw. The aerial systems employed have been both beamed and nondirectional. In the early days of these observations, the radio results were recorded by visual monitoring, but this method has gradually given way to automatic photographic recording. Meteor echoes have, as a rule, been recorded either as an amplitude-time presentation or as a range-time presentation. Range is defined as distance from the observing station. The observational data are summarized under various headings.

Rates. The number of meteors recorded by radio in a given time varies considerably with the wavelength used and the various parameters of the transmitter-receiver system. The problem of rates is a very complicated one. Broadly speaking, the meteor rate per hour varies directly as the square of the wavelength, directly as the square root of the peak transmitter power, and inversely as the square root of the minimum echo power detected on the receiver, but there are many other factors that must be taken into account (*2*).

Typical rates range from 5 to 10 meteor echoes/hr for medium-powered equipment working on a wavelength of 4 m, up to 500 to 1000 echoes/hr for high-powered equipment working on a 10-m wavelength (*3*). In the case of the shorter wavelengths, these normal rates may increase by factors up to 10 at the times of the annual meteor showers and by factors up to 1000 at the peaks of the more exceptional showers, such as the Giacobinid meteor shower of 9–10 October 1946 (*4*). It is probable that the faintest meteors generally recorded by radio methods on the longer wavelengths are around the 9th or 10th visual magnitude, in other words about one one-hundredth the brightness of the faintest meteors normally seen with the naked eye. Estimates indicate that between 10,000 and 100,000 of these radio meteors enter the earth's atmosphere every second.

From an analysis of the radio meteor rates observed on wavelengths near 10 m, it is evident that, at the time of the well-known annual meteor showers, the faint meteors do not show the same increase in rates as do the brighter visual meteors. This confirms a conclusion, already reached from an analysis of visual observations, that the meteor showers are relatively rich in the bright meteors but have lost most of the smaller particles that correspond to the meteors visible only in telescopes or by radio.

Heights. The height of meteoric ionization has been measured in a number of ways. In England, a range record is combined with a determination of angular elevation of the echo above the horizontal plane (*5*). The measurement of elevation is made by comparing the strength of the signal received on two horizontal antennas mounted at different elevations above the ground. In Canada, a three-station setup has been used, the range being determined from each station, and the height being found by a straightforward solution of the triangles involved (*6*). Methods involving the combination of visual and radio data have also been used at a number of places.

The average heights found by the different methods agree remarkably well. There is little dependence of height upon the absolute brightness of the meteor, but

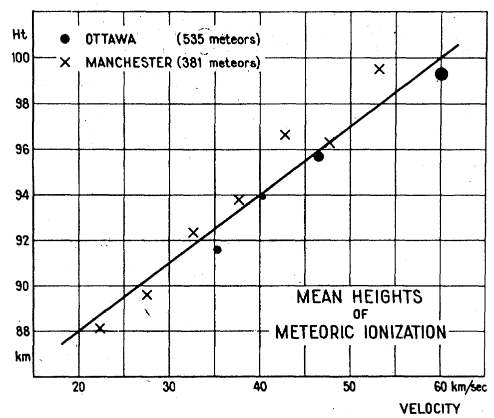

Fig 1. Mean heights of meteoric ionization.

there is a marked variation of mean height with meteor velocity. Combining more than 900 heights determined in England and Canada (*7*), we find the mean values plotted in Fig. 1. It is seen that the height for meteors moving at 60 km/sec is 100 km. This decreases linearly with velocity down to a height of 88 km for meteors with a velocity of 20 km/sec. Almost all meteoric ionization occurs in the height range of 70 to 120 km.

Velocities. It has been shown theoretically (*8, 9*) that the intensity of the radio wave reflected from the lengthening column of ionization formed by a meteor varies with a frequency dependent upon the meteor velocity and the geometry of the meteor path in relation to the observer. This amplitude variation of the received signal is usually in the audio-frequency range and has been termed the "meteor doppler whistle." It may be expressed by an equation involving Fresnel integrals and is most easily observed near the t_0 point, that is, the point where the meteor is moving perpendicularly to the line of sight. This amplitude variation can be photographically recorded and, if the range of the meteor is determined from a simultaneous range-time record, it is possible to compute the meteor velocity.

In England, a pulsed transmitting system has been used, and under these conditions the "whistle" is observed in increasing pitch after it has passed the t_0 point (*10*). In the United States and Canada, the reflected wave from a CW transmitter has been combined in the receiver with a direct ground wave, and the resulting "whistle" can be observed both before and after the meteor has passed the t_0 point (*9*). For meteors where the echo has considerable detail, it has been shown that the velocities and, in some cases, the decelerations can be measured from the range-time record alone (*11*).

Some 13,000 radio meteor velocities have now been published, approximately 11,000 in Canada and 2000 in England. The over-all velocity distributions from both sets of results, plotted in 5-km/sec steps, are illustrated in Fig. 2. They are almost identical, with velocity peaks near 37 and 60 km/sec and a mean velocity of 45 km/sec.

A number of different assumptions concerning the statistical distribution of meteor orbits in the solar system can lead to a distribution of observed velocities similar to that shown in Fig. 2, but it is still too early to draw firm conclusions (*9, 12*). Of particular significance is the fact that, within the limits of the experimental errors of these data, there are no velocities that definitely exceed the parabolic limit—that is, the upper limit of velocity that is possible for permanent members of the solar system. The radio observations take us down to objects roughly 1 mm in diameter.

Good statistical velocities have been determined by radio for nine meteor showers (*13*), and the observed frequency distributions of velocities are illustrated in Fig. 3. Four of these velocities are for daytime showers, first discovered by the English group at Manchester. Radio methods of radiant determination for meteor showers have been developed both in England (*14*) and Canada (*15*). The observed radiants (*16*) and the observed mean geocentric velocities are listed in Table 1. It must be remembered that visual or photographic observations are not generally possible in the case of the daytime meteor showers. Statistical velocities found by nonradio methods for the Perseid and Geminid showers (*17*) agree closely with the radio results.

Orbits. By combining the radio velocities with the corresponding radiants, it is possible to compute mean orbits for the various groups of meteors (*18*), and the elements of these orbits are listed in Table 2. In the case of some large meteors, it is possible to make a radio determination of the orbit of the individual particle (*19*). Except for the Perseid shower, these radio orbits are all of short period, 1.5 to 7.2 yr, and high eccentricity, 0.74 to 0.96. All but the Perseids and the Quadrantids have fairly low inclinations.

Wind velocities. At Stanford University and at the University of Manchester, the radio reflections from meteors have been used for determining statistically

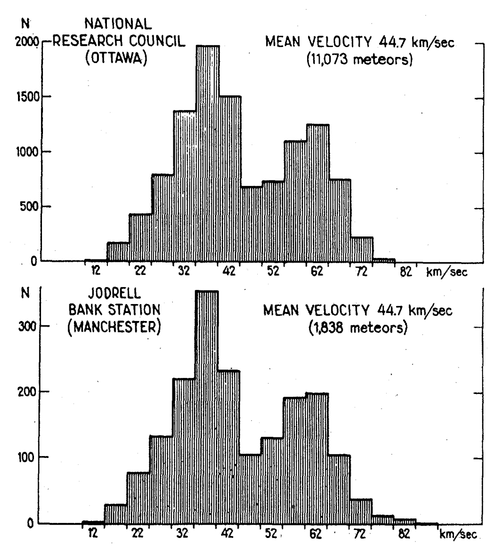

Fig. 2. Frequency distribution of meteor velocities.

the average ionospheric wind drift (*20*). Individual wind velocities of 50 m/sec in a horizontal direction and up to 10 m/sec in a vertical direction are normal. The average horizontal drift is 25 m/sec with a negligible vertical drift.

Ionospheric stratification. Evidences of fine structure or stratification in the ionosphere appear in the radio observations of meteors. The complex, long-enduring echoes usually show a series of discrete echoing ranges (*15*). The frequency distribution of the height of meteor echoes determined at Ottawa shows detail in the form of a number of submaxima. The spacing of the more marked features of this fine structure has a height difference of about 5 or 6 km and may have some statistical significance. It is similar to the preferred heights or fine structure for ionospheric reflections reported in connection with low-frequency recordings of the ionosphere (*21*). It is hard to escape the conclusion that the differential wind motions of the ionosphere, clearly evident in the long-enduring visual meteor trains, have a marked effect on the fine structure characteristics of the upper atmosphere.

Summary. To summarize, we find that the radio technique of meteor observation enables us to extend the systematic recording of meteor rates down to the 9th or 10th magnitude; to determine satisfactory heights and velocities on a scale previously impossible; to calculate the orbits of meteor showers and individual meteors, in particular those that appear only in the daytime; and to study wind drift and fine structure in the ionosphere. The radio observations have quite definitely indicated that down to the 9th magnitude, corresponding to particles approximately 1 mm in diameter, meteors are members of the solar system and do not come from interstellar space.

Table 1. Radiants and velocities of meteor showers.

Shower	Maximum	Radiant α	Radiant δ	Velocity (km/sec)
Quadrantids	3 Jan.	231°	+51°	40.9
ο Cetids (D)*	19 May	29	− 3	36.8
ζ Perseids (D)	8 June	62	+23	28.9
Arietids (D)	8 June	44	+23	38.0
β Taurids (D)	30 June	86	+19	31.4
δ Aquarids	29 July	340	−17	40.3
Perseids	12 Aug.	45	+57	60.5
Giacobinids	10 Oct.	267	+56	22.9
Geminids	12 Dec.	113	+32	35.3

* (D), daytime showers.

Table 2. Radio orbits of meteor showers.

Shower	a*	P*	e*	i*	Ω*	ω*
ο Cetids (D)†	1.3	1.5 yr	.91	34°	238°	211°
Geminids	1.4	1.7	.89	23	261	325
Arietids (D)	1.5	1.8	.94	17	77	29
ζ Perseids (D)	1.7	2.2	.80	1	77	61
δ Aquarids	1.7	2.2	.96	27	305	154
β Taurids (D)	2.4	3.7	.86	7	278	245
Giacobinids	3.5	6.6	.72	31	196	172
Quadrantids	3.7	7.2	.74	70	283	173
Perseids	(15)	(60)	.93	114	140	153

* Orbital elements: a, semimajor axis in units of earth's mean distance from the sun; P, period in years; e, eccentricity; i, inclination of orbit to ecliptic; Ω, longitude of ascending node; ω, angle from ascending node to perihelion.
† (D), daytime showers.

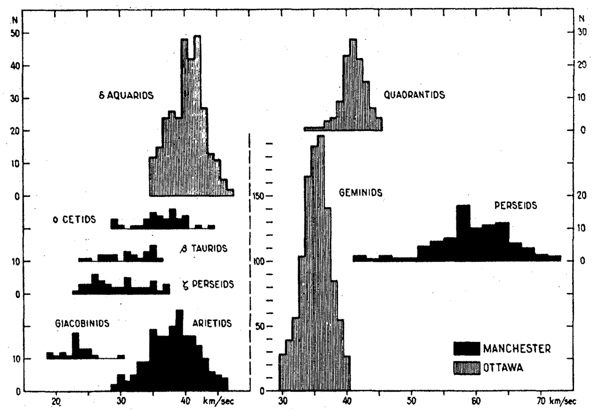

Fig. 3. Radio velocities of meteor showers.

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A New Crystalline Silica

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A STUDY (*1*) of the role of soda in the crystallization of amorphous silica under hydrothermal conditions has uncovered a new crystalline form of silica. The new phase has characteristic physical properties different from the other known forms of silica. Its occurrence in nature is not known. The resemblance of a crystalline "intermediate" in the formation of low-cristobalite from silicic acid, reported by J. Endell (*2*), has been noted and is further discussed here.

The hydrothermal conditions of formation of the new phase were produced with equipment patterned after Morey's (*3*). The reaction vessel was a Morey-type autoclave with an internal volume of approximately 20 ml. Platinum or silver crucibles, with covers, held the reactants within the autoclave. To furnish pressure, distilled water was compressed by a high-pressure hydraulic pump and delivered to the autoclave through standard high-pressure metal tubing. The pressure was maintained at desired levels by electronic controls. Heating was accomplished by surrounding the autoclave with a Nichrome-wound furnace, also controlled electronically. The gage-pressure and temperature ranges within which the new silica was synthesized were 5000 to 18,000 lb/in.^{2} and 380° to 585°C. These limits, for the most part, were set either by the equipment or by the relative sluggishness of reaction (at the lower temperatures and pressures) and, therefore, do not define actual limits between which the new silica may be synthesized.

The initial material in the majority of experiments was Merck's "analytical reagent silicic acid." Silica gel formed by the hydrolysis of tetraethyl orthosilicate was also used successfully. To this, in a platinum (or silver) crucible, was added a small amount of alkali. Distilled water was used to fill the crucible, the cover was adjusted, and water was added to fill the reaction chamber completely. The alkali was added as NaOH, KOH, LiOH, Na_2WO_4, and as the carbonates of the same metals, all in solution form. The amount added was extremely small, for example, 1 ml of 0.0100*N* NaOH solution.

The concentration of base is fairly critical, because too small an amount will cause the formation of cristobalite and too large an amount, the formation of quartz. The actual concentration in contact with the silica is not known exactly, because the distribution of water in the apparatus is so dependent on the temperature. The amount of silicic acid was not a vital factor; generally, approximately 1.5 g was used as determined by the capacity of the crucibles used. Synthesis of the new silica was effected in more than 70 experiments; conversion under optimum conditions was, in general, complete. However, crystal development usually was quite poor, the product being cryptocrystalline in appearance. Only a small proportion of experiments yielded crystals of sufficient quality for optical analysis. This strong tendency to form submicroscopic crystals may well account for its lack of recognition in nature. Identification of such crystalline aggregates in some reaction products, by means of refractive index, yielded a range of values extending from 1.501 to approximately 1.508, and also from 1.528 to approximately 1.535. These differences in index resulted from the presence of intermingled, very small crystals of either cristobalite or quartz, as determined by x-ray analysis. This effect of an "average refractive index" for an aggregate has been noted before (*4*). Consequently, another reason why the new silica may have been overlooked in nature is the lack of distinguishing features by virtue of the poor crystalline development; it may even have been identified as, or with, another phase—perhaps, as a "microcrystalline variety" of silica.

Both spectrographic and chemical analysis show the reaction product to be a very pure silica. It is completely soluble in cold hydrofluoric acid. The major impurities, Na_2O, Fe_2O_3, and Al_2O_3, are present in a concentration of less than 0.01, less than 0.02, and less than 0.02 percent, respectively. The new silica crystals