THE INNISFREE METEORITE AND THE CANADIAN CAMERA NETWORK

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ABSTRACT

The events which led to the establishment of the camera network in western Canada known as the Meteorite Observation and Recovery Project (MORP) are described. The network consists of 12 small observatories, each equipped with five cameras, a meteor detector and exposure control systems. A bright fireball was observed in Alberta and from an aircraft above clouds in Saskatchewan on February 5, 1977, at $19^h\ 17^m\ 38^s$ M.S.T. Two MORP stations in Alberta photographed the event from which a predicted impact point was calculated, leading to the recovery of a 2-kg meteorite near Innisfree, Alberta, on February 17. Five smaller pieces were located after the disappearance of snow in April. Measurements of the weak radio-activity produced by cosmic-ray activity were made on the main piece shortly after recovery at a laboratory in the United States. The results from this meteorite are of special interest because the meteor photographs provide a reliable orbit for the object before impact. Innisfree is only the third meteorite for which such a well-defined orbit is available. The low-inclination, direct orbit appears normal for asteroidal fragments which collide with the earth.

Introduction. Meteorite research in Canada received a great stimulus as a result of events which began with the fall of the Bruderheim meteorite near Edmonton, Alberta, on March 4, 1960. One recent consequence of the Bruderheim event was the photographic recording and prompt recovery of the Innisfree meteorite, which fell in Alberta on February 5, 1977, only 116 km from the much larger Bruderheim fall.

The fall and recovery of the large shower of stone meteorites north of the small town of Bruderheim has been described by Folinsbee and Bayrock (1961). Many fragments, totalling over 300 kg, of this typical hypersthene chondrite (petrologic type L6) were recovered within an elliptic area nearly 4 × 6 km in extent. This abundant supply has made possible a very extensive study of the meteorite and has provided exchange material for the improvement of the meteorite collections in Canada. The total recovered mass for Bruderheim is the largest for any Canadian meteorite.

The experience gained in field searches and laboratory study of Bruderheim was put to good use when three other meteorite falls occurred within 500 km of Edmonton in the next seven years. These meteorites were Peace River in 1963 (Folinsbee and Bayrock 1964); Revelstoke in 1965 (Folinsbee *et al.* 1967) and Vilna in 1967 (Folinsbee *et al.* 1969). These four events brought to ten the number of Canadian meteorite falls for which the

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date of fall was known and suggested that several falls per decade might be expected if reports of bright fireballs were pursued intensively. By coincidence, the next fall in Canada, the Innisfree meteorite, occurred ten years to the day (almost to the hour) after the Vilna event. Several other meteorites classified as "finds" rather than "falls" were recovered during the decade but information on the date of fall is not available in these cases.

The Bruderheim event had other, less obvious results. The collection of the fallen meteorites and their acquisition for scientific study had been handled efficiently because of the presence and interest of amateur astronomers within the Edmonton Centre of the Royal Astronomical Society of Canada and geologists at the University of Alberta and the Research Council of Alberta. In many parts of Canada the event might have gone unnoticed. This realization led directly to the establishment in 1960 of the Associate Committee on Meteorites by the National Research Council of Canada to stimulate interest in all aspects of meteorite research. The Committee consists of about fifteen members chosen to give broad geographic coverage across Canada. One of the Committee's first actions was to organize a national system for the prompt reporting of fireballs to the regional representatives and the central office in Ottawa, a system which worked well for Innisfree.

Another early action of the Associate Committee was to recommend the creation of a network of photographic stations in western Canada to record bright fireballs. The aim of such networks is to provide accurate data on the atmospheric trajectory, from which the probable impact point of meteorites on the ground can be calculated with more confidence and less delay than by the collection and analysis of eyewitness reports. Secondly, the data from the upper end of the luminous path can be used to calculate the orbit of the meteoroid around the sun before it collided with the earth. The observational data may also be used for statistical studies of the rate of occurrence of bright meteors, orbital statistics of large meteoroids in the solar system, etc.

Photographs of the atmospheric flight of the Pribram meteorite in Czechoslovakia had been secured in 1959 with conventional meteor cameras (Ceplecha 1961). In 1961 the International Astronomical Union approved a resolution calling for the construction of photographic fireball networks and the first two networks were established about 1964 in Czechoslovakia (Ceplecha and Rajchl 1965) and the central plains of the United States (McCrosky and Boeschenstein 1965). The Czechoslovakian network soon expanded in cooperation with West Germany and is known as the European Network. The Canadian Meteorite Observation and Recovery Project (MORP) became the third such project (Halliday 1973), followed more recently by networks in the United Kingdom (Hindley 1975) and in the U.S.S.R. (Zotkin *et al.* 1976).

The Meteorite Observation and Recovery Project.

History of the Project. Since the purpose of meteorite networks is to recover meteorites for which the astronomical data have been secured, networks should be located to provide a large amount of clear night-sky conditions over a terrain which is suitable for a meteorite search. Although Canada has a very large land area, the only region of adequate size which meets the second requirement is the agricultural region of the three prairie provinces. Clear weather is expected to be as frequent here as elsewhere in Canada and one of the by-products of the project is data on clear night-sky conditions. Preliminary data on these conditions are presented at the end of this section.

The planning and construction of the MORP network were accomplished in the late 1960s within the Astronomy Division of the Dominion Observatory, then a Branch of the Department of Energy, Mines and Resources. Some preliminary site searches began in the summer of 1966 with eight of the final observatory sites selected in 1967 and the remaining four in the spring of 1968. One potential site was later shifted ten kilometres when it was found the land would not support a loaded cement truck. The network was planned to keep all stations away from the glare of large cities and sites were selected to be near existing power lines and away from roads with heavy traffic. Where possible, however, they were chosen to be not far from major highways and local habitation, the latter in order to derive some protection against potential vandalism. Figure 1 shows the location of the twelve observatories where the station names refer to nearby towns, usually within 10 km of the station. Table I lists the geographic locations and elevations of the stations; the elevations include a height of 4 m above ground for the cameras.

The MORP network is operated from a field headquarters on the campus of the University of Saskatchewan in Saskatoon, near the geographic centre of the network. The Asquith observatory, west of Saskatoon, was chosen as the first station and its small building was erected during the summer of 1968. Some modifications were introduced into the building design before two more observatories were built the following winter, then seven stations in the summer of 1969 and, finally, the two Manitoba observatories during the winter of 1969–70. The first cameras were installed at Asquith late in 1968 but the network was not effectively operational on a routine basis until 1971.

FIG. 1—Map of the MORP network showing the location of the twelve stations (filled circles) and the site of the Innisfree meteorite fall relative to some major cities (open stars) and highways in western Canada. The effective search area for meteorites is about 700,000 km^2.

TABLE I

LOCATIONS OF THE MORP STATIONS

Station	Latitude	Longitude	Elevation (metres)
A Asquith	52°12′04″ N	107°07′04″ W	527
B Neilburg	52 41 25	109 36 11	651
C Vegreville	53 32 03	112 06 45	640
D Lousana	52 07 42	113 11 48	929
E Brooks	50 29 53	111 53 15	774
F Leader	50 54 01	109 37 01	677
G Ernfold	50 31 18	106 51 04	710
H Lajord	50 16 21	104 09 28	600
I Langenburg	50 44 51	101 43 08	512
J Alonsa	50 44 36	99 03 31	287
K Birch River	52 24 06	101 00 49	277
L Watson	52 01 29	104 34 21	533

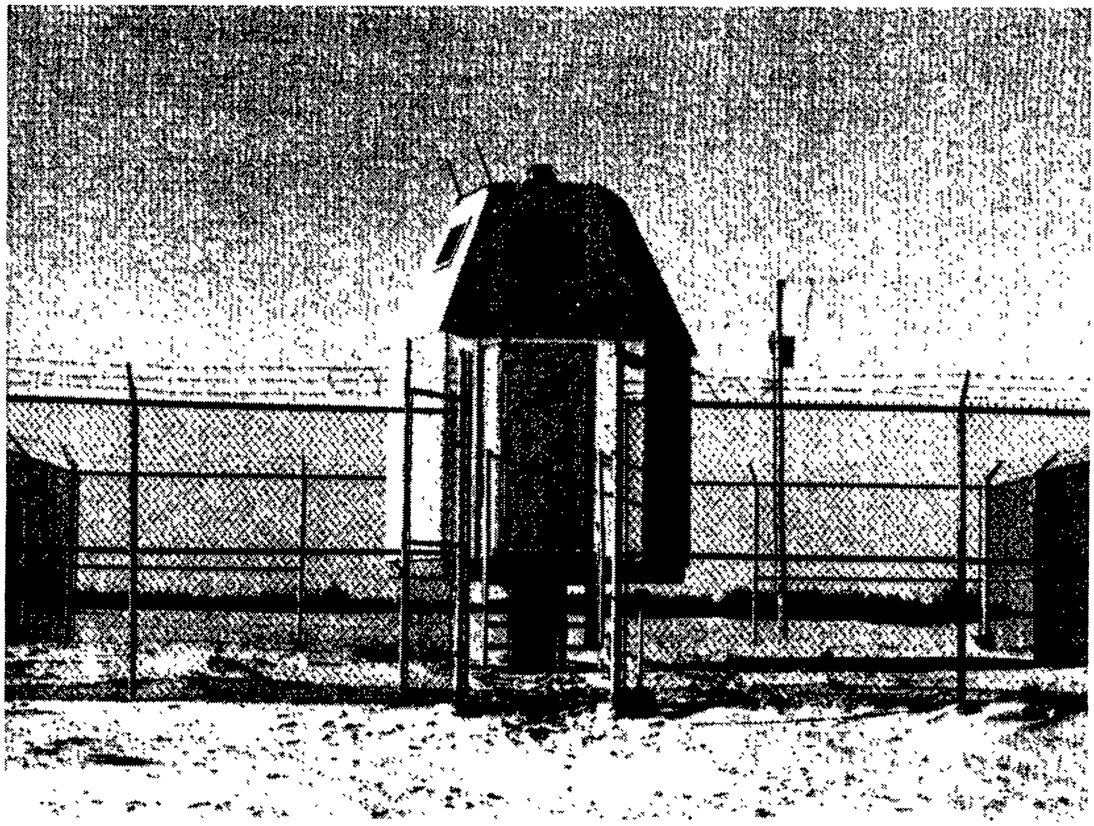

FIG. 2—The exterior of the MORP observatory near Langenburg, Saskatchewan. Note the meteor detector mounted on the roof of the building.

Observatories. Consideration of the area of sky covered by one camera led to a decision to use five cameras per station, each covering about 54° of azimuth near the horizon. The cameras are positioned with the lower edges of their fields of view only 1° or 2° above the horizon and the upper edges near a mean elevation of 55°. The unobserved zenith area of each station is surveyed by neighbouring stations, but small triangular areas between the fields of adjacent cameras and the horizon are not covered. The protective buildings were chosen to be pentagons in spite of some slight concern that local contractors might not be familiar with 72° and 108° combinations. Figure 2 shows the exterior of one of the observatories under typical winter conditions with a modest snow cover on the ground.

The observatory floor area is only 6.5 m^2. The roof has an almost flat central section, on which is mounted the meteor detector described below, and five sides which slope at 23° to the vertical. Each window has an area of 1900 cm^2 and is coated with a transparent but conductive coating which carries a few amperes of low-voltage a.c. power to keep the surface free of ice and dew. The building is heated or cooled, as necessary, by a combination heater and air conditioner. A security fence encloses the building and it has been a great relief that during the eight years of their existence, problems of vandalism and intrusion have been negligible at the observatories.

The cameras are mounted on a steel frame which is bolted to a concrete pedestal about 2.5 m above the floor. The pedestal goes down into the ground about 2 m and there opens into a flat base. This structure provides a very stable mounting for the cameras, independent of building vibrations. The floor is an integral part of the concrete pedestal about 1.5 m above ground; one result of this is that the building stands fairly high above the ground surface and turbulent dust- or snow-laden winds flow more easily past the building and cause less obscuration of the sky. Another result is that snowdrifts almost never block the door.

Cameras. The MORP cameras were specially manufactured by the Charles A. Hulcher Company of Hampton, Virginia, and use wide-angle Super-Komura 50-mm lenses. The film used is Kodak 70-mm Plus-X Pan in 100-foot rolls on the dimensionally stable Estar base. Each picture has, in the margin between frames, a camera identifier (station letter A to L and camera number 1 to 5) and three fiducial marks (see figure 3). Each fiducial mark consists of a 60-micron dot surrounded by four radial arms calling attention to it and the marks can be used to interrelate the measurements of two pictures from the same camera. This is useful if a meteor is photographed adequately itself but the picture lacks sufficient stars because of thin clouds or haze. One camera at each station records in one corner of the frame the time of the end of each exposure. Originally, time was recorded by a Bulova "accutron" clock with a 24-hour dial and a 999-day calendar, but a conversion to digital time displays is now in progress.

Each camera has been tested to determine the distortion in the pictures, since each lens has its own unique distortion pattern. The test setup in a gymnasium involved a horizontal array of forty precisely spaced lights, sufficiently distant from the camera to leave the focus at infinity. By tilting the camera, about thirty successive superimposed exposures were made until the entire frame of film was covered with a matrix of dots. Measurements of the dots were used to construct a contour map of the distortion, from which by interpolation a set of 841 pairs of numbers was extracted, representing displacement in X and Y co-ordinates all over the field. The computer program which calculates orbits and impact points looks up the distortion file of the relevant camera and adjusts all measurements to allow for this effect of the lens.

The cameras have a "sun shutter" in front of the lens to protect the lens

FIG. 3—Photograph taken during a thunderstorm, looking north from Lousana, Alberta. One nearby lightning flash contrasts with the numerous cloud-to-earth flashes in the background. This photo is from camera D1 (camera 1 at station D) the same camera that later secured one of the photos of the Innisfree meteorite. The clock image records the time of the end of the exposure.

during daytime and a "masking shutter" which is normally open and closes only during film advances to prevent star images appearing dragged across the picture. The cameras also have a "chopping shutter", as is usual in meteor cameras, to break the meteor trail four times each second in order to give timed intervals on the trail photograph for use in determining velocity. The chopping shutter in the MORP cameras is a rotating wheel driven by a synchronous motor, but it is unique in having three equal sectors of different opacities. One sector is completely transparent and this is the only one that transmits significant starlight. Another sector is made of filter material of density 5.0 (and supposedly neutral as to colour) which blocks out all but a most unusually bright meteor and has blocked out every meteor seen to date by the MORP cameras. The third sector has neutral density 2.0 (a reduction, in astronomical terms, of 5 mag) and will transmit enough light from a very bright meteor to make an image that may be more suitable for measurement than the overexposed image that came through the transparent sector. The masking shutter and the chopping shutter are both near the focal plane.

Meteor Detector. It is desirable to know the time of occurrence of each photographed meteor since the time is required in an exact calculation of the orbit. The problem is how to detect the occurrence. The meteors of interest are bright, but not in comparison to the sum of all light coming from the sky. Most meteors move within a limited range of angular velocities and this motion is their most distinctive characteristic. The MORP "meteor detector", designed by Spar Aerospace Products Limited of Toronto, looks for this motion. It consists of a light-sensitive photomultiplier tube (abbreviated PMT, model RCA 2067) above which are two coaxial cones of perforated metal, one larger and completely covering the other. The PMT produces a current proportional to the incident light. Any light that reaches the PMT must pass through holes in both cones and light from a moving source such as a meteor will find different combinations of holes in quick succession. The output of the PMT will then have a rapidly varying component. The PMT is connected to an electronic filter that passes only the range of frequencies from 1 to 10 Hz which has been deemed appropriate, based on typical meteor velocities and the geometry of the meteor detector. Therefore, provided only that the meteor has enough brightness to stand out above the integrated background level, the system can detect it and respond by printing the time of the event and advancing the film after a delay to ensure the meteor is not still in flight. This should protect what is expected to be a valuable picture. All pictures show the time at which the exposure ended, the only difference in the case of there having been a meteor signal is the appearance of a large marker at the edge of the frame (to upper left of the clock image in figure 3).

The meteor detector is tested about once a month by the station operator, who shoots up a small rocket flare of the type used for distress signals. The test is not a perfect simulation of a meteor, because at a distance sufficient to properly diminish the brightness the entire flight of the flare would be below the field of view of the meteor detector (since the detector does not look down to the horizon in order to avoid vehicle lights). The operator gets an indication that the system is working from a brief flash of the building entrance light.

Exposure Control. The electronics which control the camera operation were designed and produced by SED Systems Limited of Saskatoon. It is desirable to get as much exposure time on each frame as possible, but not to the point where a meteor image already on the film, or one about to arrive, would be obscured by overall fogging. An exposure control system determines the time at which each picture will end. Light from the northern sky (to avoid moonlight) falls on a silicon photodiode, but first the light has been interrupted at a 100-Hz frequency by a driven-tuning-fork type of beam chopper. The current through the photodiode is proportional to the light brightness and because of the chopper it is an alternating current, which is convenient to amplify. After amplification, the signal is rectified by a synchronous transistor switch and the resulting half-wave is integrated by an operational amplifier. The output of the op-amp is a voltage which increases at a rate proportional to the area of the half-wave. When this voltage reaches a certain level it triggers a pulse of current from another op-amp. The result is that the interval between these pulses is proportional to the sky brightness. The pulses are counted and when a preset number of the order of a few hundred is reached, the film is advanced. Except for inaccuracies due to non-linearity of circuit responses, the time to reach a certain number of pulses will be proportional to the total accumulation of exposure on the film.

The pulses from the exposure control circuit are also used to determine when cameras should start and stop each day. As long as the rate of pulses exceeds a certain limit (about one pulse per second) the light level is so high that the resulting short exposures are uneconomical, i.e. less than 10 to 15 minutes in length. As the light decreases after sunset, the cameras are turned on when the pulse rate is slow enough; conversely, before sunrise the pulse rate increases and at the shut-down point the cameras, the meteor detector and the exposure-control circuit are de-activated for the day. The length of exposures will normally vary from about 10 minutes to 3 hours. To minimize loss of data due to electronic failures, there are safeguard circuits which prevent film-advance rates of more than two pictures in 20 minutes and limit the duration of any exposure to a maximum of 200 minutes.

Routine Procedures. Each observatory is visited about twice a week by an operator who lives near the station. Local residents were trained for this in a few hours and with the aid of a manual that covers routine and extraordinary procedures, these operators do an excellent job. In the entire history of the project only one operator resigned (he was transferred by his regular employer) and one passed the job to his son.

The operators push certain switches to elicit responses from the system that indicate correct or improper functioning. They tune to WWV radio time signals and at a precise minute they push a switch to expose the clock on the film. In this way, when their reports are compared with the times read on the film, a continuous monitoring of clock errors is possible.

The 100-foot rolls of film last from three to six weeks, depending on the length of the nights at various seasons. The operators change the film when necessary and mail it to the Saskatoon headquarters of MORP in reusable aluminum cylinders. If a meteor of interest is reported by eyewitnesses, the exposed film may be removed prematurely and rushed to Saskatoon for prompt examination. The film is processed in an automatic processor that handles three rolls of film at a time, requiring three hours to a batch. After processing, the film is mounted on a five-film viewer especially built for this purpose. The five rolls that were exposed at one station at the same time are synchronized on this machine, since the time that applies to all five is recorded on only one of the films.

Each frame is examined for meteors and for data on sky conditions with the information entered directly at a computer terminal. The picture is considered to be subdivided into four parts, upper and lower portions of both left and right sides. The upper fields are that portion above 20° elevation while the lower fields are the portion between 8° and 20° in elevation. The criterion for classifying sky as clear is good visibility of star trails and the data are divided into half-hour intervals in the computer analysis with the predominant characteristic of an interval ascribed to the whole interval. The twenty areas of sky thus recorded for each station are used by the computer to calculate the total area of atmosphere, at an assumed height of 70 km, under observation by the network at any time. This data will eventually be combined with data on the distribution of observed meteors in order to derive meteor flux values.

Incidental Observations. A photographic monitoring of the sky will inevitably garner pictures of more than just meteors. The MORP cameras have provided some useful pre-discovery observations of a nova (Blackwell *et al.* 1975). The films have been searched for bursts of light that were at one time predicted to be associated with gamma-ray bursts (to no avail and the suspected association has now been virtually abandoned). They have *never* seen what is usually called an Unidentified Flying Object and surely this negative evidence should be considered in any discussion about the reality of UFOs. They have recorded some rather interesting – in fact, beautiful – pictures of lightning such as the example reproduced in figure 3.

The MORP cameras have also shown that, contrary to a widely-held belief, the sky in western Canada is not particularly clear and cloud-free.

As data began to accumulate, it became evident that the number of hours of good observing was less than expected. An analysis is now available for about 1000 days from March 1974 to December 1976. The numbers derived are the number of half-hour intervals during which the sky was clear or cloudy at each of twelve typical locations in the agricultural area of western Canada. The following information has been extracted from about 64,000 station-hours of observing. The distribution by categories of sky condition is:

Category A – *virtually no clouds* above 8° elevation during a half-hour interval. 13%

Category B – *partly cloudy*, but in at least one of ten azimuthal sectors there is a patch of clear sky above 20° elevation lasting at least one-half hour. This category includes observations that would have been in category A except that some instrumental problem prevented a complete observation. Experience leads to the opinion that such problems should transfer about 4 percentage points from category B to category A. 22%

Category C – *completely cloudy* so that there was not even one sector that was clear for one-half hour. Instrumental problems enter to a small extent – if the sky had been clear in one small part which happened to be missed by a faulty camera, then an interval that should have just barely qualified as category B would have been reported as category C. We believe this situation should transfer less than 2 percentage points from category C to B. 65%

The revised statistics, based on these adjustments for instrumental problems are:

Category A – virtually no clouds	17%
Category B – partly cloudy	20%
Category C – completely cloudy	63%

Before MORP was established, information about cloudiness was obtained from Environment Canada, as it is now known. The data at the available locations nearest to the MORP stations indicated the percentages of conditions as follows:

Category 1 – completely clear to 29% cloudy	42%
Category 2 – from 30% to 79% cloudy	16%
Category 3 – from 80% to 100% cloudy	42%

The MORP categories do not coincide with the Meteorological Branch's categories, but one way to compare the two is by noting that category 3 is less frequent than category C, even though the former is much less restrictive than the latter (up to 20% of the sky may be clear for category 3 but sky better than about 3% clear would be taken into category B rather than C). In looking for explanations of the discrepancy, we note that the Environment Canada observations are made at 2300 and 0500 hours. Perhaps there is a systematic tendency for the sky to cloud over after 2300 hours or clear before 0500 hours. Another possibility is that the years 1974 to 1977 were cloudier than the years 1951 to 1960. Cloud statistics are merely a peripheral interest of MORP but these observations are noted here in case they may be of interest to meteorologists. More data are available on request.

The Fall of the Innisfree Meteorite.

Visual Observations. Camera networks provide more accurate data on the paths of bright meteors than do even a large number of visual observers but reports from eyewitnesses may be crucial in initiating prompt action. In the MORP system an unreported bright meteor might not be found on the films for over a month, so it is important to learn quickly that an interesting fireball has been seen. A bright fireball may be seen over such a large area that reports of it may follow a variety of routes before reaching interested scientists. Such was the case with the Innisfree fireball.

Among the groups of Canadians whose help in reporting bright meteors has been requested by the Associate Committee on Meteorites are airline pilots and crew. Obviously pilots are in a position to see the night sky above clouds and away from city lights. The crew of Air Canada's flight 167 from Winnipeg to Vancouver on February 5, 1977, observed the Innisfree fireball above clouds near Swift Current, Saskatchewan, about 470 km from the meteor. They gave a description of the event by radio to the control tower in Regina, which was promptly relayed to Mr. John Hodges of that city, a member of the Associate Committee for many years. He telephoned the staff of the MORP office in Saskatoon who immediately took action to call in the films from a few stations expected to be the ones of interest for the event. Since weather conditions in Saskatchewan were generally cloudy, local observations from the Saskatoon area would not have alerted the staff as quickly.

In Alberta the sky was clear and reports from observers near Edmonton were directed to Professor R. E. Folinsbee, initially as a result of interviews by the Fort Saskatchewan Detachment of the Royal Canadian Mounted Police. Rural police forces are another valuable source of information on spectacular events and the Associate Committee has routinely sought their help. An appeal over local radio stations for observations produced more than a hundred responses of which seventeen with some possible value have been generously made available to us by Professor Folinsbee. Two other reports, one being the observation from the aircraft, were received in Ottawa through the reporting system.

Anticipating knowledge of the actual meteor path derived from the photographs we find that these visual reports come from distances varying between 2 and 304 km from the sub-meteor point at the time of maximum light. Six observers at four different locations were within 30 km of the ground path and an additional six were between 50 and 100 km distant.

One of the more lengthy reports is the result of an interview by the R.C.M.P. with Miss Brendalee Walker, age 13, who lives on a farm near Chipman, Alberta, about 77 km from the ground point beneath maximum meteor light. The report was made within an hour or two of the observation and is given here in full.

> It was approximately 7:15 p.m. 5 February, 1977, and I was standing outside of the farmhouse, near the woodbox. Our farm is $1^1/_2$ miles north, 2 miles east and $1^1/_2$ miles north of Chipman, Alberta. I was looking north and I saw what appeared to be car lights shining off our gas tank, and when I looked up the whole east sky was lit up. There was a large spark and about six little ones trailing. They were heading east. They were all pure white and very bright. The large one was about the size of a large car and the rest were only small, about the size of basketballs. They were all in a straight line, going east and appeared to be only about 50 feet over the top of the trees. I don't have any idea how fast they were going. I saw them for at least 30 seconds and they were still moving when I got to the house. The sparks appeared to be falling pretty rapidly and were something like a plane landing. The sparks appeared to be travelling about 40 miles per hour.

Although it is not part of the verbatim report the accompanying police report quotes Miss Walker as also saying a swishing sound *accompanied the lights* but there was no large sonic boom. She did, however, run into her home long before these latter sounds would have had time to reach her. From the photographic record it is clear that the duration has been greatly overestimated in this report, which is a very common tendency. At the location of the observer the path would have appeared steeply inclined to the horizon with maximum light at an elevation near 24° in a direction 16° south of the easterly direction described. The similarity to an aircraft landing is enhanced by the low angular velocity (about $6° \, s^{-1}$) for this observer.

Two other youthful observers of the Innisfree meteorite fall, Lyell and Martin Ferguson, ages about 10 and 8 years, were much the closest of any in the group of witnesses to the actual meteor path. They were walking south on a road about 14 km north-northeast of Innisfree when the sky lit up behind them. One of them turned around to look for an approaching car but the fireball was so nearly overhead he did not see it until he was again facing south, when he observed fragments descending high in the sky in front of him. From the photographic record it is deduced they were within 2 km of the sub-meteor path, almost under the brightest point on the trail. There is some disparity in their estimates of just where the light disappeared but their favorable location minimizes the uncertainty involved. Both boys described a sonic boom "like distant shooting dying away to the southeast about $1^1/_2$ minutes after the fireball".

The only other convincing report of sounds was an observation by Mr. Ken McGillivray who was located somewhat northeast of the town of Innisfree, about 11 km from the late portions of the sub-meteor path. He described two large fragments plus six to eight small ones, and after going in the farmhouse to describe the meteor to members of the family, he again went outside. By repeating his actions an interval of 1 minute 45 seconds was found between the meteor and the sound, described as "a rumble, then a sharp rumble, mellowed rumbling for 15 seconds, loud, then 5 seconds dying away". Another witness, in a schoolyard only a kilometre more distant from the path, heard no sounds.

The report of "swishing" sounds by Miss Walker may be a valid observation of the anomalous sounds which sometimes accompany the luminous phenomenon (Lamar and Romig 1964). Without confirmation from other observers this must remain doubtful. The more usual sounds of rumbling or distant explosions were definitely heard but apparently only in a small area near the end of the trail. It appears that the sounds were much less impressive than those recorded for many other meteoritic events. Reports of colour were few, with the "pure white" of Miss Walker's report, "a large red ball" by one of the nearby observers and finally a blue flash described by a person who was indoors with a window facing away from the actual meteor.

An analysis of all the visual observations would certainly have led searchers to the right area, due in considerable measure to a fortunate spacing of a few observers very close to the end-point and on opposite sides of the path. The visual end-point would appear to be defined within a circle of radius about 10 km, centred close to the actual location of the fallen meteorites. This is several kilometres beyond the point where the photographic trails end, but it is reasonable to suppose a nearby visual observer would have followed fragments to a lower luminosity than the MORP cameras.

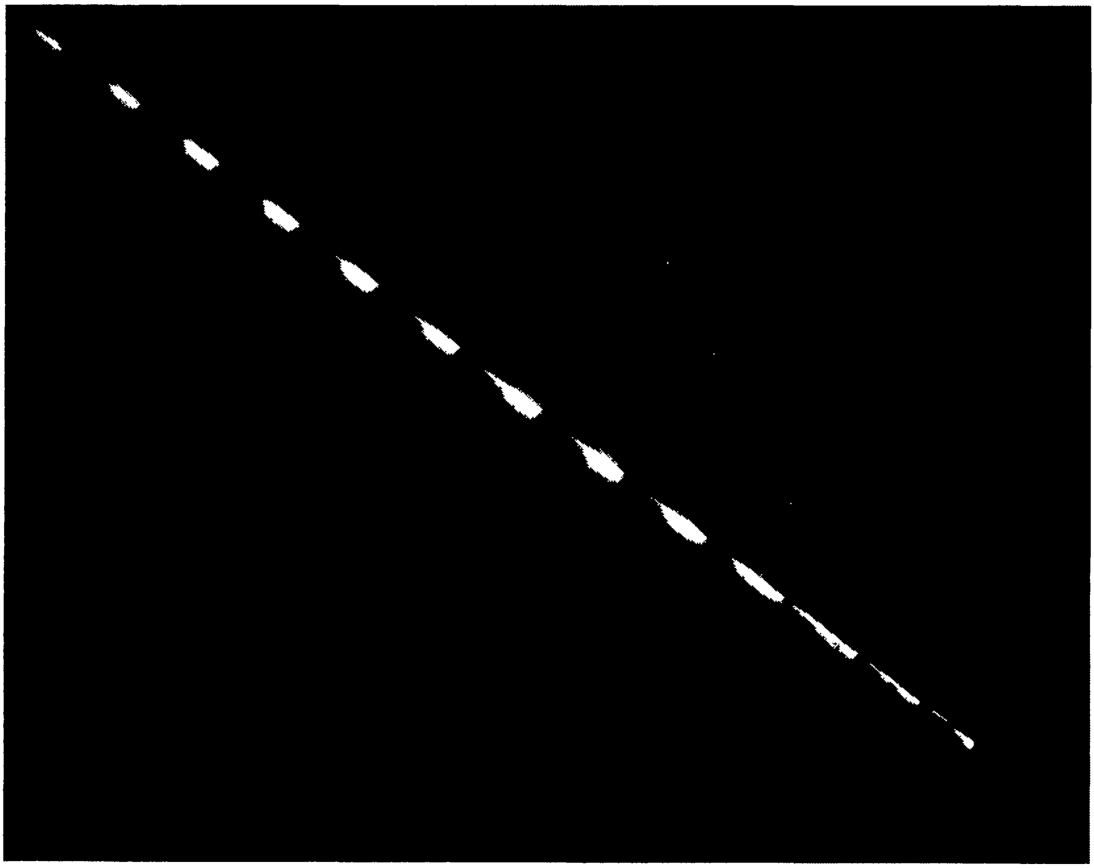

FIG. 4—The Innisfree meteorite in flight, from upper left to lower right, photographed from the MORP station at Vegreville. The rotating filter wheel produces 4 segments of trail per second. The bright stars crossing the meteor trail near the middle are Castor and Pollux. Note the evidence of separate fragments low on the path. The meteor entered the field at a height of 59 km and was observed over a path length of 37.8° in 3.82 seconds.

Photographic Observations. As a result of the visual report from the Air Canada aircraft, the films from the four stations Watson, Asquith, Neilburg and Vegreville (see figure 1) were called in for immediate processing. The weather at the three Saskatchewan stations had been cloudy but the Vegreville films produced the bright meteor shown in figure 4. The early portion of the trail was lost in the station's blind spot above altitudes of 55° but nearly four seconds duration of trail was recorded. Near the bottom, several distinct fragments are visible and a significant decrease in angular velocity suggests a similar decrease in the linear velocity, an essential requirement for the survival of fragments as meteorites. The meteor detector at Vegreville had been activated by the fireball, establishing the exact time of some early portion of the bright part of the trail as 1977, 6 February, $02^h\ 17^m\ 38^s$ U.T.

The main hope of obtaining a photograph from a second station now shifted to the Lousana station with some chance that the Brooks station might also have recorded it. Since it was known that the operator at Lousana was temporarily absent, Eldon Hubbs from the MORP office in Saskatoon made the long drive to Lousana and back on the same day to retrieve the films. When they were processed, a faint meteor image was found on the first exposure of the evening. Unfortunately this exposure suffered so severely from twilight sky fog that the only star image on the frame was a short trail of Polaris. Careful transposition of star trails from the next frame via the fiducial marks provided an adequate reference background for measurement of the meteor position. The meteor as seen from Brooks would have been lost in one of the small triangular areas between two camera fields and the horizon; however, it might not have been bright enough to be recorded at this station in any case, if conditions were not ideal. No other stations secured photographs so we are left with the minimum coverage for a complete reduction, i.e. two stations.

The two meteor photographs were measured in Saskatoon and the measures relayed to Ottawa by telephone. Due to minor modifications to the computer program it was temporarily not possible to run the program in Saskatoon. On February 14th, computations on the N.R.C. computer in Ottawa indicated an end-point for the longest surviving fragment near a height of 20 km and a terminal velocity well below 4 km s^{-1}. These values are very similar to the terminal values for the Lost City meteorite, 19-km height and 3.5 km s^{-1} (McCrosky *et al.* 1971), and thus provided the first evidence that a meteorite fall was probable. Programs of fireball photography have shown that many spectacularly bright meteors end at heights and velocities which are so high that the survival of any material larger than dust particles is unlikely. Until the height and velocity values were available on February 14 the fireball of February 5 was merely one of a group of several interesting fireballs photographed by the network, but the survival of this object to such a great depth in the atmosphere made an immediate search desirable.

Meteorite Search. Before initiating the field search, solutions of the dark-flight portion of the trajectory (below 20 km) were performed for three hypothetical meteorite sizes. The data on the atmospheric wind profile recorded at Edmonton about three hours before the meteor were used. The solution employs these data together with the known gravity and rotational values for the earth and calculates step by step the displacement due to these effects plus the ballistic drag for a spherical object falling through air of known density at each height. The body size is represented by a mass-to-area ratio and values appropriate for stone meteorites of masses 10, 4 and 0.5 kg were chosen, in the belief that pieces in this range might have survived and be in observable locations. Owing to two favorable aspects of the event, namely that the wind was essentially a tail wind which tends to keep smaller pieces from drifting far behind larger ones, combined with a steep path for the fireball (elevation of the apparent radiant 68°), the spread between the three hypothetical fragments was only 2 km on the ground. The predicted area of fall was in farming country about 13 km northeast of the small town of Innisfree which is situated on the main highway from Edmonton to Saskatoon.

On February 16 two of the authors, Halliday and Griffin, flew from Ottawa to Edmonton and proceeded to Vegreville by car while Blackwell and Eldon Hubbs drove from Saskatoon, stopping en route to assess the snow conditions in the predicted fall area. The fields were covered with 20 to 40 cm of moderately packed snow except on exposed knolls where the wind had reduced the snow cover and recent sunshine had begun to expose rocks and clumps of soil. Conditions appeared suitable for a search by snowmobile so that evening arrangements were made with young snow-mobilers from Vegreville to begin a search the following morning.

The search began at 10:30 a.m. on February 17, using four machines, three of them driven by local youths with the authors of this paper as passengers while the fourth was driven by Eldon Hubbs. Weather conditions were quite mild with daytime temperatures near +5°C which caused some concern about overheating the engines and required minimum cruising speeds near 25 km hr^{-1}. Traverses were run with spacings varying from 12 to 18 metres between successive runs, depending on the amount of stubble or other material breaking the snow surface.

The normal unit of agricultural area in western Canada is a quarter section, a square 0.5 mile on a side (805 metres), so individual traverses were generally of this length unless blocked by obstacles such as small patches of deciduous bush. With four machines it required an hour to cover each quarter section. Frequent stops were made to examine field stones, clumps of soil which appeared quite black due to the absorption of melted snow, and disturbances caused by the burrows of small animals. At 4 p.m. Halliday spotted a dark object some 5 or 6 metres to one side of the snowmobile track which, on circling back to examine it, proved to be the main piece of the meteorite resting on the snow, surrounded by 0.5 metre of dirty snow (see figure 5). Evidently the meteorite had penetrated the 30 cm of snow to the frozen soil and rebounded to the surface, bringing up some

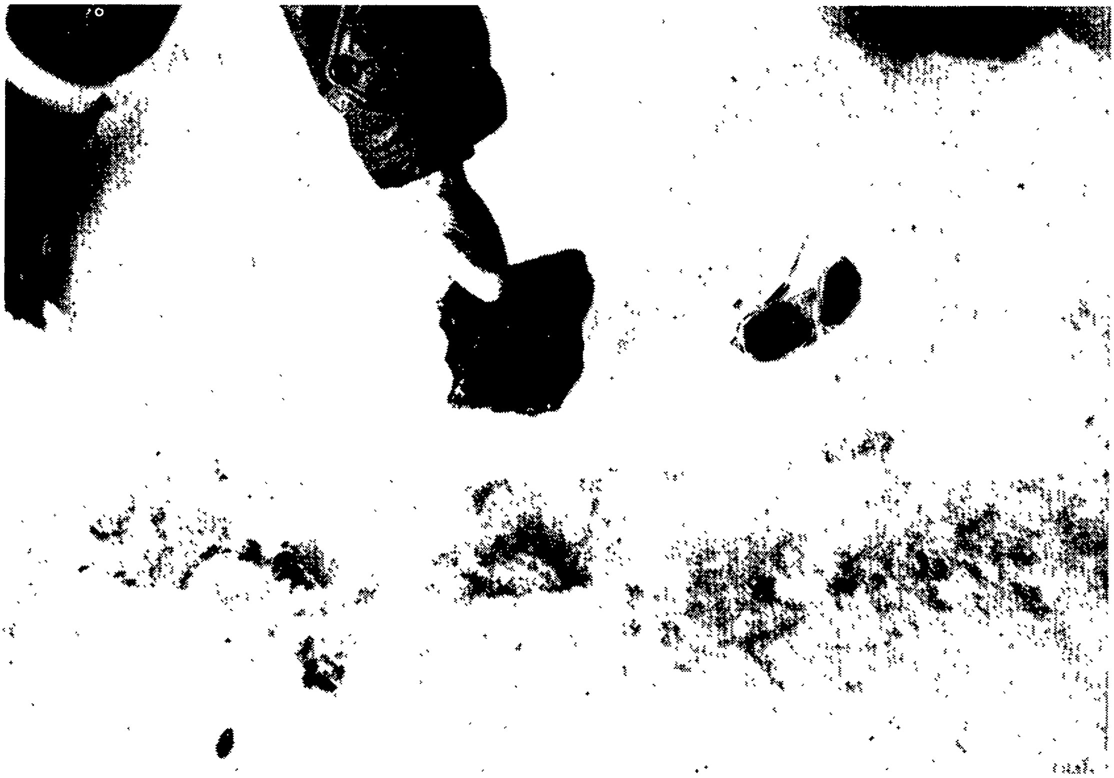

FIG. 5—The main mass of the Innisfree meteorite is shown held just above the spot where it came to rest on the snow. Some dirt and meteorite chips are scattered around the spot as a result of bouncing off the field beneath the snow.

soil and knocking a few small chips off the meteorite. The meteorite was buried about half its own depth in the snow and would probably soon have been buried more deeply due to warming of the black exterior in sunshine.

The discovery of a meteorite in the field is a more concrete event than most scientific discoveries. The feeling of elation which accompanied the event may have been partially due to this effect but was more directly related to the fact that after nearly eleven years of planning, construction and operation of the camera network, a meteorite had now been observed and recovered very much according to the original plans. The meteorite was found during the search of the fourth quarter section after only four hours of actual searching, slightly less than twelve days after its fall. Figure 6 shows the search team at the site of the find.

The following day an agreement was signed with Mr. William Fedechko, owner of the land on which the meteorite was found, for the purchase of the meteorite "for a fair price to be determined after preliminary study of the meteorite". Accurate measurements were made of the location of the meteorite fall and the search was continued, with particular attention given to areas further along the path where somewhat larger pieces would be

FIG. 6—Six of the seven members of the search team shown with the four snowmobiles used in the search. From left to right, E. Hubbs, V. Kuzz, A. T. Blackwell, K. Fried, I. Halliday and M. Freed, with the photo taken by A. A. Griffin. The meteorite is seen in front of the third snowmobile from left, a small haversack used to protect the camera and maps lies to the left of the meteorite.

expected if they existed. The weight of the first specimen was 2.07 kg which, at the time, left doubt as to whether it was the largest surviving fragment. Nine quarter sections (5.8 km^2) were searched by snowmobile but no other pieces were found. Professor Folinsbee and his students made a particular effort to locate areas where very small fragments (0.1 to 1-g range) might have been carried by the wind, but none was found. In consultation with Dr. Folinsbee it was agreed to propose the name "Innisfree" for the meteorite, in accord with the usual practice of choosing the name of a nearby town or village not previously used for naming another meteorite.

Careful study of the Vegreville photograph during March showed that at least five fragments had survived below an altitude of 25 km and probably something had reached the ground from each of these pieces, in addition to smaller pieces which would not appear individually on the photograph. The search effort was renewed in April once the snow had disappeared. A group of students led by Professor Folinsbee searched on April 9 and located a small piece of total mass 33 grams, although it was fractured into many pieces. Its location was 600 metres back up the path from the original find, on land owned by a neighbour of Mr. Fedechko. Three days later Mr. Fedechko notified the MORP office in Saskatoon that three pieces with a combined weight in excess of a kilogram had been found by his family and some visitors, all on the same quarter section as the original find. It appears that two of these were found on April 10 and the largest of the three on April 11. The MORP staff from Saskatoon returned to Innisfree the following week and a sixth piece of the meteorite was found by Blackwell on April 21. It was in numerous fragments, apparently the result of having been run over by a farm implement used in plowing a firebreak. The first piece found by the Fedechkos was in two fragments and the smaller of these was distributed as souvenirs, so the total weight of this piece, estimated as 120 grams, is uncertain. Pieces 4, 5 and 6, in order of discovery, weighed 345, 894 and 330 grams. The total recovered mass is 3.79 kg and the mean coordinates of the fall are 111° 20′ 15″ W, 53° 24′ 54″ N. Major portions of the Innisfree fall will be located in the National Meteorite Collection at the Geological Survey of Canada, Ottawa, and in the collection of the University of Alberta, Edmonton.

Detailed study of the relationship between the pieces and the individual trails on the Vegreville photograph will be reported elsewhere. It is believed the five main pieces can be identified individually with the five trails observed on the photograph. The "ellipse of fall" is small, an area 400 by 500 metres can enclose the location of all the finds. The centre of this area is only 300 metres from the point predicted on February 14 for a 4-kg piece, the point which was used as a rough centre of interest in the original search.

The experience gained in the Innisfree search leads us to certain conclusions. Frozen soil is obviously a great advantage in keeping kilogram-size meteorites from burying themselves in the ground. The dark-flight computation indicates the large piece struck the ground with a velocity near 70 m s^{-1} (157 m.p.h.) and required 130 seconds to fall after the light went out. The rebound phenomenon was especially helpful for this 2-kg specimen. If the smaller pieces also rebounded, then they were subsequently obscured by the snow before the search in February. A similar rebound effect was observed for some of the Bruderheim stones and also in at least one witnessed fall in the U.S.S.R. (A. N. Simonenko, personal communication). Meteorite searches on foot may be effective, as in the case of the later pieces of Lost City (McCrosky *et al.* 1971) but the time required to search an area of several square kilometres is very large. For winter searches we believe snowmobiles offer a great advantage in agricultural areas, especially if the location can be determined before fresh snowfalls occur. The sixth piece of Innisfree was found by an observer on the roof of a station wagon which was cruising slowly across the field. The added height for the observer above the ground is beneficial, even for quite small meteorites and we recommend this method where possible for searches on grazing areas or plowed fields.

It may be of interest to speculate on the role played by winter conditions on meteorite recovery in Canada. Innisfree is the eleventh Canadian ''fall'' for which the exact date of the event is known, as opposed to ''finds'' in which a meteorite is discovered by accident. If we ignore the three early falls before 1905 when population patterns were much different from the present, then the modern falls are: Dresden, Ontario, July 1939; Benton, New Brunswick, January 1949; Abee, Alberta, June 1952; Bruderheim, Alberta, March 1960; Peace River, Alberta, March 1963; Revelstoke, British Columbia, March 1965; Vilna, Alberta, February 1967; Innisfree, Alberta, February 1977. Six of these eight events were winter falls on snow-covered terrain. For Bruderheim, Revelstoke and Vilna, some or all of the meteoritic material was recovered from the ice on lakes or rivers. Two other Canadian meteorites, Great Bear Lake (June 1936) and Holman Island (March 1951) were recovered from seasonal ice surfaces so, although they are finds rather than falls, the ice conditions were a vital factor in their recovery and establish the dates of the fall within a few months. A survey of worldwide dates of meteorite falls shows no preference for northern hemisphere winter months so the apparent preponderance of winter events among Canadian falls is attributed to a better chance of recovery when frozen soil and ice leave the meteorites in a more visible situation.

The Innisfree Meteorite.

Description. The Innisfree meteorite is a rather normal stone meteorite of the low-iron (L-type) or hypersthene chondrite group. Detailed classification is not yet complete and the final designation may be L4 or L5 although it may prove not to be typical of any one subclass. The individual pieces were covered with the usual thin, black fusion crust, about 0.3 mm in thickness. Most pieces were of a chunky shape with rather flat sides and angular corners. There is no obvious indication that the pieces fit together and they would not be expected to fit, since study of the meteor photograph indicates they separated at a variety of heights while ablation was still very active. One face of the main piece shows an area of partial fusion crust

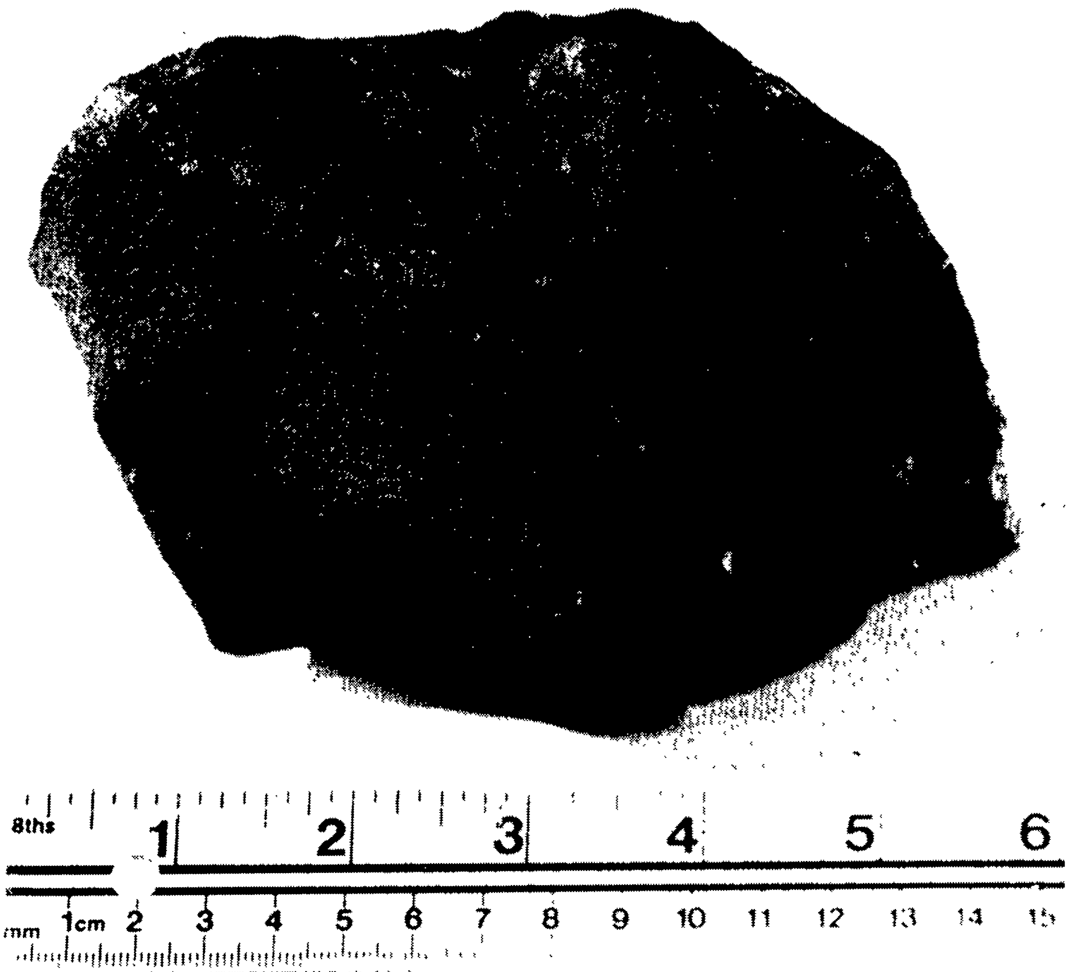

FIG. 7—The 2-kg piece of the meteorite photographed seven hours after recovery. The dark fusion crust exhibits a fine pebbled texture on the vertical face, a network of hairline cracks on the upper surface and a potential fracture near the corner in the right background. The scale shows inches (upper) and cm (lower).

where a thin layer may have broken off when the velocity was just too low to generate a fresh crust. Figure 7 shows a view of the main piece photographed late on February 17, 1977, about seven hours after it was found.

Various types of technical studies have been undertaken on samples of the Innisfree meteorite at different laboratories in several countries and the results will appear in technical journals. One important class of study is the

TABLE II

ORBIT OF INNISFREE METEORITE

Semi-major axis	a	1.872 AU
Eccentricity	e	0.4732
Inclination	i	12.27°
Argument of perihelion	ω	177.97°
Longitude of asc. node	θ	316.80°
Perihelion distance	q	0.986 AU
Aphelion distance	q'	2.758 AU
Period	P	2.561 yr

measurement of the weak radioactivity produced in the meteorite in space by the bombardment of cosmic rays. There is a very wide range of half-lives for the isotopes which may be produced so it is important to have such measures made as soon as possible after a fresh meteorite is recovered. For this reason the main mass of the meteorite was taken by Halliday to the Battelle Pacific Northwest Laboratories in Richland, Washington, on February 19 and measures of the radiation began exactly two weeks after the fall of the meteorite. These measures have revealed at least one interesting anomaly in Innisfree, indicating it has been subjected to a high level of cosmic radiation in the relatively recent past (Rancitelli and Laul 1977).

The Orbit. Pribram, Lost City and Innisfree are the three meteorites for which two-station photography provides a reliable orbit and much of the interest in Innisfree depends on this fact. The cosmic-ray effects mentioned in the previous section are of much greater interest when the recent orbit of the meteorite is known and the same is true for studies of thermal effects to which the meteorite has been subjected in space.

The Innisfree meteorite entered the atmosphere with a velocity of 14.5 km s^{-1} from a geocentric radiant, corrected for earth rotation and gravity, at $\alpha_{1950} = 6.66°$, $\delta_{1950} = 66.21°$. The orbital elements derived from these data are listed in Table II and the orbit is shown in figure 8 relative to the orbits of the inner planets. The orbits of Pribram and Lost City are also shown, neglecting the modest inclinations of the meteorite orbits. Innisfree had a low-inclination, direct orbit with perihelion very close to the earth's orbit and aphelion well beyond Mars, in the asteroid belt. It is typical of the orbits believed to pertain to meteorites in general, for which an asteroidal origin is increasingly supported by current research.

Many of the numerical quantities relating to the fireball and the fragments of the Innisfree meteorite are collected together in Table III for convenience.

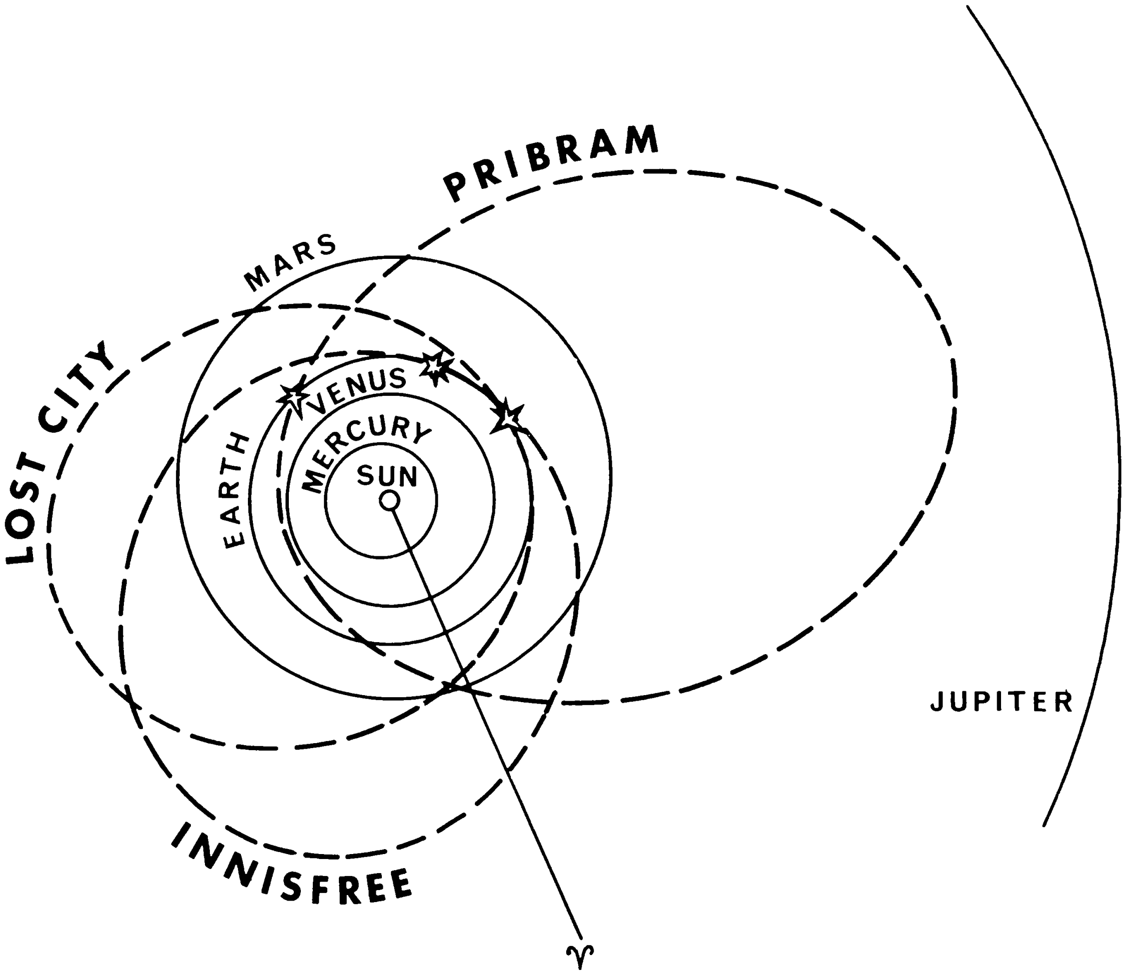

FIG. 8—The orbits of the Pribram, Lost City and Innisfree meteorites are shown projected on the ecliptic plane relative to the orbits of the five inner planets. The direction to the first point of Aries is also indicated.

TABLE III

SUMMARY OF DATA ON INNISFREE METEORITE

Time of meteor	1977, February 6, $02^h\ 17^m\ 38^s$ U.T.
Recovery of first piece	1977, February 17, 23^h U.T.
Mean co-ordinates of fall	$\phi = 53°24'54''$ N; $\lambda = 111°20'15''$ W
Masses of fragments	2.07; 0.033; 0.120; 0.345; 0.894; 0.330 kg
Total mass recovered	3.79 kg
Pre-atmospheric velocity	14.54 km s^{-1}
Terminal velocities from photos (five fragments)	2.7 to 4.7 km s^{-1}
Beginning height (Lousana)	62.4 km
End height (Vegreville)	19.9 km
Duration of photographed trail	4.09 s
Corrected geocentric radiant (1950)	$\alpha = 6.66°$; $\delta = 66.21°$
Elevation of apparent radiant	67.8°

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