GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 2, PAGES 164-167, FEBRUARY 1987

REPLY TO SOTER

L. A. Frank, J. B. Sigwarth, and J. D. Craven

Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

Soter (1986) claims that the detection rate of the small comets proposed by Frank et al. (1986a) must be about 250 events per hour with the M.I.T. space surveillance telescope (Taff, 1981; 1986). We find that Soter grossly overestimates this detection rate by not recognizing the importance of (1) the minimum of cometary fluxes during the observing period with the telescope and (2) the broad range of possible physical properties of these small comets.

We first establish the overall character of the temporal variation of the fluxes of the proposed small comets during the period of early November through late-January. A correlation of this variation with that for radar meteor rates is then used to firmly associate the objects observed by Dynamics Explorer 1 with an extraterrestrial origin. We next examine the expected range of physical properties and estimate the brightness of these objects. From considerations of these temporal variations and physical properties we find that the most probable range for the detection rate for these small comets is ~ 0.1 to 1 event/hour with the M.I.T. surveillance telescope during January. These rates are not inconsistent with the observations with the optical telescope.

We begin with a discussion of the temporal variations of comet fluxes in the vicinity of the earth. Because of the requirement to observe the same area in the earth's sunlit hemisphere for an extended period of time, ~ months, and the conflicting constraints of the motion of the spacecraft's apogee in latitude and the orbital plane in local time, the determination of temporal variations is difficult. Additionally the telemetry coverage for the spacecraft must be exceptionally good due to the low occurrence rates of the atmospheric holes. However one such period of observations occurs during 1 November 1981 through 21 January 1982. The occurrence rates are determined for an area bounded by earth-centered solar-ecliptic latitudes $30° \leq \theta_{SE} \leq 90°$ and longitudes $285° \leq \phi_{SE} \leq 315°$, i.e., at moderate and high latitudes over the Northern Hemisphere in the local morning sector. The corresponding area is 1.1×10^7 km^2. The area of interest is partitioned into 24 smaller and equal areas. If the viewing from the spacecraft does not cover the entire area in a single image then the occurrence rate is determined by finding the rate for the fraction of the 24 area segments in view and subsequently normalizing to the composite area. The criterion for identification of an atmospheric hole remains identical to that employed for previous studies, i.e., a decrease in intensity corresponding to a decrease in sensor count rates by $\geq 4.3\ \sigma$ where σ is the standard deviation for the mean of adjacent samples (cf. Frank et al., 1986b).

The occurrence rates of atmospheric holes are shown in Figure 1 for the period 1 November 1981 through 21 January 1982. The viewing geometry after 21 January is inadequate to obtain useful occurrence rates. These rates are given in units of events/minute for the specified area of 1.1×10^7 km^2. In order to achieve useful event statistics, averages are taken for two-day intervals. Approximately 50 or more images are used to determine the rates for each of these two-day periods. The standard deviation, $\pm\ \sigma$, for each rate determination is also indicated in Figure 1. Large temporal variations in the occurrence rates of atmospheric holes are seen in Figure 1. A general decline of rates by a factor of ~ 10 is found with comparison of those for the early-November period with the minimum rates in mid-January. This overall decline exhibits considerable fluctuations on shorter time scales, e.g., the decrease on about 14 December. Thus the existence of temporal fluctuations for the rates of atmospheric holes is established with this fortuitous series of observations.

We now provide evidence that the temporal variations of atmospheric holes are attributable to an extraterrestrial source, and not due to atmospheric dayglow irregularities of local origins, for example. In order to establish a relationship of the above temporal fluctuations of atmospheric holes with radar meteor rates at similar latitudes, we use the forward-scatter radar observations from a location near Ottawa, Canada as reported by Vogan and Campbell (1957). These radar meteor rates are shown for the period 1 November 1955 to 21 January 1956 in the bottom panel of Figure 1. These are hourly average rates, i.e., non-shower and shower events for a 24-hour period. Because simultaneous observations with Dynamics Explorer 1 and the radar meteor station are not available in the literature, we assume that the annual radar meteor rates are qualitatively similar from year to year, with expectations of yearly fluctuations in the amplitudes of the major meteor showers (cf. McKinley, 1961). We attempt to separate the non-shower event rates from those dominated by the presence of meteor showers by indicating the periods for five major meteor showers during this period with shaded zones and open circles in Figure 1. Identification of shower events associated with the Northern Taurids is qualitative and is implemented by noting that the rates significantly differ on five days from the running mean. The local times of radiant transit for the five major shower events are ~ 0055 (Northern Taurids), 0624 (Leonids), 0205 (Geminids), 0825 (Ursids) and 0835 (Quadrantids). The comet associations are Comet Encke with the Northern Taurids, Comet Tempel with the Leonids and Comet Tuttle with the Ursids. Non-shower radar meteor rates are indi-

Paper number 6L6394.
0094-8276/87/006L-6394$03.00

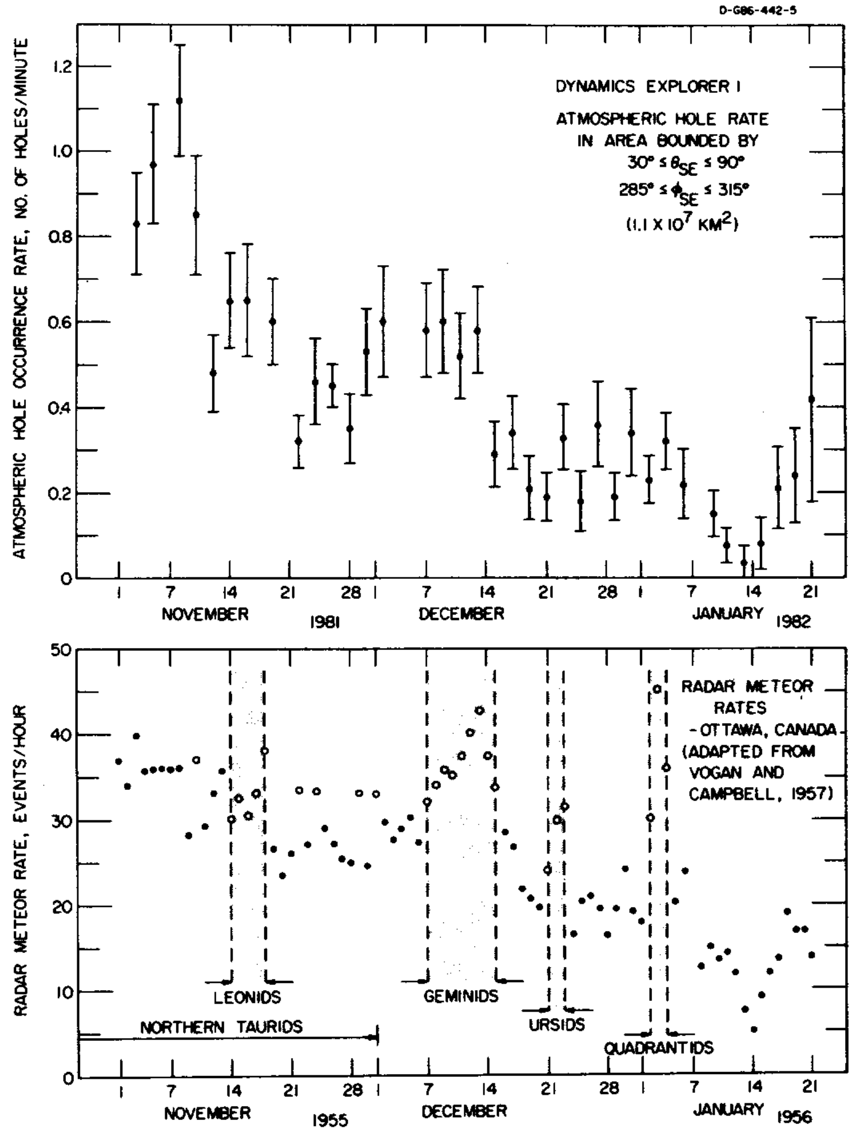

Fig. 1. Average occurrence rates of atmospheric holes during the period November 1981 through late-January 1982 (upper panel). Radar meteor rates reported by Vogan and Campbell (1957) for the same months but for earlier years 1955 and 1956 (lower panel).

cated by the closed circles in Figure 1. The correlation of these rates with those of the atmospheric holes is remarkable, e.g., the overall decrease in meteor rates by a factor of ~ 10 over the period 1 November to mid-January, the minimum of mid-January with subsequent recovery, the decrease in fluxes on ~ 8 November, and the period of more-or-less constant fluxes during ~ 20 December to 6 January. However, the event rates for the two types of phenomena differ substantially. If we estimate the effective area for the detection of radar meteors as ~ 5×10^4 km^2, then for a radar rate of ~ 35 events/hour (early November), the corresponding rate of atmospheric holes in this area is ~ 0.2 atmospheric holes/hour.

The local times for the radiant crossings for the major meteor showers are such that these radiant positions as projected into the atmosphere intersect the sampled area only for the Ursids and Quadrantids. The Quadrantids are circumpolar. Examination of Figure 1 shows that no increases in atmospheric hole rates are seen with the appearance of these two major meteor showers. Thus the conclusion could be made that the meteor showers and atmospheric holes are unrelated with the important qualification that the shower rates are comparable during these two different years. If this conclusion is valid then the small comets associated with atmospheric holes are a class of solar system objects that would appear to be distinct from debris from the large, well-known comets.

The effective area, A, of the telescope for the detection of these small comets can be estimated for the anticipated ranges of sizes and the optical characteristics of the surface. The apparent visual brightness of the small comets, M_c, as seen from the earth's surface is given by (Allen, 1973)

$$M_c = M_s + 5 \log(r/R) - 2.5 \log p + \Phi(\alpha) \qquad (1)$$

where M_s is the apparent blue magnitude of the sun, r is the distance from the telescope to the

TABLE I. Anticipated Hourly Detection Rates of Small Comets with the M.I.T. Surveillance Telescope

R = 6 meters; p = 0.02

Early November

	M_V = 18	17	16	15	14	13
$\Phi(\alpha)$ = 2	680	270	110	43	17	6.8
3	270	110	43	17	6.8	2.7
4	110	43	17	6.8	2.7	1.1
5	43	17	6.8	2.7	1.1	0.43
6	17	6.8	2.7	1.1	0.43	0.17
7	6.8	2.7	1.1	0.43	0.17	0.07

Mid-January

	M_V = 18	17	16	15	14	13
$\Phi(\alpha)$ = 2	68	27	11	4.3	1.7	0.68
3	27	11	4.3	1.7	0.68	0.27
4	11	4.3	1.7	0.68	0.27	0.11
5	4.3	1.7	0.68	0.27	0.11	0.04
6	1.7	0.68	0.27	0.11	0.04	0.02
7	0.68	0.27	0.11	0.04	0.02	0.01

R = 4 meters; p = 0.005

Early November

	M_V = 18	17	16	15	14	13
$\Phi(\alpha)$ = 2	75	30	12	4.8	1.9	0.75
3	30	12	4.8	1.9	0.75	0.30
4	12	4.8	1.9	0.75	0.30	0.12
5	4.8	1.9	0.75	0.30	0.12	0.05
6	1.9	0.75	0.30	0.12	0.05	0.02
7	0.75	0.30	0.12	0.05	0.02	0.01

Mid-January

	M_V = 18	17	16	15	14	13
$\Phi(\alpha)$ = 2	7.5	3.0	1.2	0.48	0.19	0.08
3	3.0	1.2	0.48	0.19	0.08	0.03
4	1.2	0.48	0.19	0.08	0.03	0.01
5	0.48	0.19	0.08	0.03	0.01	0.00
6	0.19	0.08	0.03	0.01	0.00	0.00
7	0.08	0.03	0.01	0.00	0.00	0.00

comet, R is the radius of the comet, p is the ratio of comet brightness at phase angle $\alpha = 0°$ to the brightness of a perfectly diffusing disk with the same diameter and position, and $\Phi(\alpha)$ is the phase law in magnitudes. The magnitude of the sun is −26.1. If the threshold sensitivity of the telescope is M_V in magnitudes, a limiting distance r (max) for observing the small comets can be determined by setting $M_V = M_C$. The event rate C seen by the telescope is then

$$C \simeq FA \sin(\beta) \simeq (F/2)(r(\max))^2 \, \theta \sin(\beta) \qquad (2)$$

where F is the flux of small comets in the vicinity of the earth, θ is the angular width of the telescope's field of view ($\theta = 1.2° = 2.1 \times 10^{-2}$ rad), and β is the angle of attack to the effective area of viewing. Because telescopic viewing occurs during twilight hours we take $\beta = 30°$ for our estimates.

The event rate C for the telescope can be determined if F, M_V, R, p and $\Phi(\alpha)$ in equations (1) and (2) are known.

(1) The comet fluxes F for the two periods early November and mid-January are determined from the observations shown in Figure 1. These fluxes are $\sim 7.2 \times 10^{-10}$ and $\sim 7.2 \times 10^{-11}/\text{km}^2$-sec, respectively. At these distances from the earth, gravitational focusing is neglected.

(2) The threshold magnitude M_V for routine telescopic surveys is 16.5 (L. G. Taff, private communication, 1986; Taff et al., 1985; Taff, 1986). The telescope can also be operated at a threshold of 17.7 (Taff, 1986). Observations at twilight can be degraded by 1 or 2 magnitudes for these thresholds (Taff, 1986).

(3) The comet radius R is estimated by Frank et al. (1986a) with the assumption that the density of the water snow is 0.1 gm/cm^3. This radius is 6 m. If the density is 0.3 gm/cm^3, then R = 4 m.

(4) The reflectance parameter p is expected to be similar to the diffuse reflectance of various carbon blacks (cf. Frank et al., 1986c) and in the range of ~ 0.01 to 0.02 (cf. Wolfe, 1978). Observations of the dark crust on the nucleus of Comet Halley indicate that values for the geometric albedo can be as low as ~ 2% or less (Keller et al., 1986).

(5) The phase law $\Phi(\alpha)$ in magnitudes is unknown for comets. For twilight viewing, $\alpha \simeq 90°$, Soter (1986) uses the value 3.3 from measurements of the Martian moons Phobos and Deimos. An anticipated range for $\Phi(\alpha)$ of ~ 3 to 5 at phase angles $\alpha \simeq 70°$ to 110° appears to be reasonable (cf. Lumme and Bowell, 1981).

The expected event rates for the detection of small comets with the telescope can now be calculated. These event rates are summarized in the four tables that comprise Table I. The upper two tables give the hourly detection rates for small comets with radius R of 6 m and reflectance parameter p = 0.02. The results for R = 4 m and p = 0.005 are found in the bottom two tables. The hourly rates for the two periods early November and mid-January are also shown. Hourly rates are given as functions of the threshold magnitude M_V of the telescope and the phase law $\Phi(\alpha)$. Most probable values for these hourly rates from our above discussion of parameter values are boxed in the tables. The corresponding range of r(max) is ~ 5,000 to 56,000 km.

Observations with the telescope by Taff (1986) are taken in the months of January and February. The observed rate for the detection of the more distant objects in the vicinity of the earth with the telescope during tens of hours of observing time is about 3 to 5 events/hour (L. G. Taff, private communication, 1986). These objects are interpreted by Taff as satellites or their debris in distant orbits. However, the variations of the light curves for some of these objects do not exhibit the periodic fluctuations of an actively maintained, rotating spacecraft (Taff, 1986). The distance to these objects cannot be determined by their parallax with the observatory's two telescopes because their positions are beyond ~ 1,000 km. The expected detection rate of small comets for this time period is in the range of 0.1 to 1 event/hour (right-hand tables of Table I). Thus such rates are not inconsistent with the telescope observations.

Now we discuss the observation of the comets at low altitudes (cf. Soter, 1986). Frank et al. (1986a,d) infer that these small comets fragment at altitudes estimated to be in the range of ~ 1,000 to 3,000 km. For at least a brief period after fragmentation, these small comets are anticipated to be relatively bright. The angular motion is in the range of ~ 10^3 to 10^4 μrad/sec. These angular motions are sufficiently large to produce a streak during a 1/30-second exposure time for the telescope. Order-of-magnitude estimates for the detection rates of these small comets at low altitudes, from equation (2) and with $F = 1.4 \times 10^{-10}$ comets/km^2-sec from gravitational focusing, are one event every 40 and 360 hours for r(max) of 3,000 and 1,000 km, respectively. The hourly rates for streaks due to satellites and meteors in telescope frames are ~ 20 events/hour (Taff, 1986). Thus one of ~ 800 to 7200 such streaks would be due to the passage of a small comet. Identification of this streak thus requires the tedious examination of thousands of streaks in the image frames. No study of this type is reported.

Soter (1986) states that the small comets should be detected in the image frames used in the searches for earth-approaching asteroids. This assumption appears to be incorrect. The asteroid searches are implemented by taking two image frames separated in time sufficiently to detect the motion of an asteroid. Apparent angular motion is ~ 5×10^{-2} μrad/sec and the elapsed time between frames is $\gtrsim$ 1,000 sec. The angular motions of the small comets are sufficiently large, ~ 10 to 10^3 μrad/sec, that these objects are beyond the field-of-view for at least one of the frames. Thus these objects are not to be seen in two consecutive frames for the asteroid searches.

It should be noted that the detection of the proposed small comets appears possible, e.g., with a dedicated survey during early November when the cometary fluxes are high. Such a survey is not known to us. Other facilities such as the Spacewatch Camera (Gehrels and McMillan, 1982; Gehrels, 1985) and the Palomar Schmidt camera (Helin and Shoemaker, 1979), that are also employed for asteroid and comet searches, may prove useful for this survey.

In summary Soter (1986) overestimates the detection rates of the proposed small comets with the M.I.T. space surveillance telescope by factors of ~ 10^2 to 10^3. This discrepancy is due to disregard of (1) the minimum of cometary fluxes during the telescope observing period and (2) the range of likely physical characteristics of the small comets. Simply stated, the proposed small comets are difficult, but not impossible to detect with optical telescopes. The observations reported by Taff (1986) as cited by Soter (1986) are not inconsistent with the proposed large fluxes of small comets in the vicinity of the earth.

Acknowledgements. The authors express their appreciation to L. G. Taff for a discussion of the capabilities of the GEODSS telescopes. This research was supported in part by NASA under grants NAG5-483 and NGL-16-001-002 and by ONR under grant N00014-85-K-0404.

References

Allen, C. W., Astrophysical Quantities, The Athlone Press, University of London, p. 142, 1973.

Frank, L. A., J. B. Sigwarth and J. D. Craven, On the influx of small comets into the earth's upper atmosphere, II. Interpretation, Geophys. Res. Lett., 13, 307, 1986a.

Frank, L. A., J. B. Sigwarth and J. D. Craven, On the influx of small comets into the earth's upper atmosphere, I. Observations, Geophys. Res. Lett., 13, 303, 1986b.

Frank, L. A., J. B. Sigwarth and J. D. Craven, Reply, Geophys. Res. Lett., 13, 703, 1986c.

Frank, L. A., J. B. Sigwarth and J. D. Craven, Reply, Geophys. Res. Lett., 13, 985, 1986d.

Gehrels, T., Asteroids and comets, Physics Today, 38(2), 33, 1985.

Gehrels, T. and R. S. McMillan, CCD scanning for asteroids and comets, in Sun and Planetary System, ed. by W. Fricke and G. Teleki, Reidel Publishing Co., Dordrecht, Holland, p. 279, 1982.

Helin, E. F. and E. M. Shoemaker, The Palomar planet-crossing asteroid survey, 1973-1978, Icarus, 40, 321, 1979.

Keller, H. U., et al., First Halley Multicolour Camera imaging results from Giotto, Nature, 321, 320, 1986.

Lumme, K. and E. Bowell, Radiative transfer in the surfaces of atmosphereless bodies. II. Interpretation of phase curves, Astron. J., 86, 1705, 1981.

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

Soter, S., Comment, Geophys. Res. Lett., (this issue), 1986.

Taff, L. G., A new asteroid observation and search technique, Pub. Astron. Soc. Pacific, 93, 658, 1981.

Taff, L. G., Satellite debris: recent measurements, J. Spacecraft, 23, 342, 1986.

Taff, L. G., D. E. Beatty, A. J. Yakutis and P. M. S. Randall, Low altitude, one centimeter, space debris search at Lincoln Laboratory's (M. I. T.) Experimental Test System, Adv. Space Res., 5(2), 35, 1985.

Vogan, E. L. and L. L. Campbell, Meteor signal rates observed in forward-scatter, Canad. J. Phys., 35, 1176, 1957.

Wolfe, W. L., Properties of optical materials, in Handbook of Optics, ed. by W. G. Driscoll and W. Vaughan, Optical Soc. Am., McGraw-Hill, New York, p. 7-140, 1978.

(Accepted October 3, 1986.)