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THE DETECTION OF A DUST TRAIL IN THE ORBIT OF AN EARTH-THREATENING LONG-PERIOD COMET

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ABSTRACT

IRAS has detected dust trails in the orbit of short-period comets but has been unable to detect such trails in the orbit of long-period comets. We now present observations from the study of a meteor outburst that identify the event as being due to just that. Ten orbits of meteoroids were measured during a brief but intense outburst of the α Monocerotid shower that confirm the theory that a trail of dust is brought occasionally in collision with the Earth by planetary perturbations. Observations of this event by multiple meteor observing techniques provide the first direct measurement of the size distribution of dust in a comet dust trail, the dust density in the trail of a long-period comet, and a cross section of such a trail in the path of Earth. The implication for detecting potential Earth-threatening long-period comets by their meteoric signature is discussed.

Subject headings: comets: general — dust, extinction — meteors, meteoroids

1. INTRODUCTION

Meteor outbursts are known from numerous ancient chronicles as among the most impressive phenomena in the night sky (Imoto & Hasegawa 1958; Tian-shan 1977; Hughes 1982). They are brief enhancements of meteor stream activity that stand out from the normal annual rates. They occur when Earth traverses the dusty remains of what must be relatively recent cometary ejecta that has not yet spread far and wide enough to cause an annual meteor stream. Most intriguing are the outbursts that happen without warning, when the parent body is far from perihelion, because these far-comet–type outbursts (Jenniskens 1995a) have never been observed with modern meteor observing techniques.

We report now on the first successful orchestrated attempt to observe such an event, an outburst of the α Monocerotid stream. Chance visual observers had seen rich displays of this stream in 1925, 1935, and 1985 (Olivier 1926, 1936; Ducoty 1986). Mentioned by Olivier (1936) as perhaps being due to a cloud of matter with a 10 year orbital period, Kresák (1958) argued that a short-period retrograde orbit was unlikely and suggested that, instead, a "meteoric ring" was displaced by planetary perturbations causing accidental encounters with Earth. Indeed, Plavec (1955) had shown that dust trails are a consequence of the relatively small ejection velocities in Whipple's comet ejection model (Whipple 1951). Such dust trails were first observed by *IRAS* in the orbit of several short-period comets (Sykes et al. 1986). A link between these comet dust trails and the near-comet–type meteor outbursts, associated with short-period comets, has subsequently been proposed (Kresák 1993; Jenniskens 1995a).

Until now, no evidence was available to support the hypothesis that far-comet–type outbursts are due to Earth traversing a comet dust trail. In fact, the more recent discussions on the cause of far-comet–type outbursts favor the presence of clouds of debris with short orbital period (e.g. Porubčan & Štohl 1992; Porubčan, Štohl, & Soreň 1992). In contrast, we found recently that far-comet–type outbursts return in a pattern that reflects the position of the major planets, which gives weight to the dust trail hypothesis (Jenniskens 1997) and implies a different physical mechanism for the cause of far-comet–type meteor outbursts than those of near-comet–type. We predicted a recurrence of the α Monocerotid outburst on 1995 November 22 between 0 and 6 hr UT, when Jupiter and Saturn would be positioned in much the same way as in 1935 (Jenniskens 1995b).

That stream was caught in the act, and the outburst was recorded by photographic, low–light-level TV, radio forward meteor scatter and visual techniques. We can confirm now that the dust particles have a long orbital period, demonstrating that this far-comet–type meteor outburst is caused by a trail of dust in the orbit of a long-period comet. A comet that can approach Earth's orbit dangerously close.

2. OBSERVATIONS

In search of clear weather, five temporary photographic meteor stations were established in the province of Andalusia, Spain, near the villages of Almedinilla, Zafarraya, Alcudia-de-Gaudix, and Chirivel and at the Calar Alto Observatory (Betlem et al. 1996). At each site, batteries of 12 small 35 mm cameras with f1.8/50 mm optics were employed, equipped with crystal oscillator controlled rotating shutters. Low–light-level TV imaging was performed at Zafarraya (K. Jobse) and Almedinilla (J. van't Leven). All stations provided visual support. Twenty-three trained amateur meteor observers of the Dutch Meteor Society participated in this event, supported by seven members of the Spanish Meteor Society SOMYCE at the site in Chirivel (L. R. Bellot Rubio c.s.). A selection of images of α Monocerotid meteors recorded by photographic and TV image intensified techniques, including a small section of life video,

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can be found on the World Wide Web homepage of the Dutch Meteor Society (http://www.pi.net/~terkuile/meteors/dms.htm).

At the same time, meteors were counted by radio forward meteor scattering (MS) (Weitzen & Ralston 1988), with systems in Finland (I. Yrjölä in Kuusankoski) and in the Netherlands (P. Bus in Groningen and T. Schoenmaker in Roden). Typically, a two to three element Yagi antenna was aimed low in the sky toward a (series of) strong 86–92 MHz transmittter(s) at some 1000 km distance, and threshold crossings of the carrier wave were counted automatically or were recorded on a chart recorder. The radio MS reflection counts of individual systems ranged between 400 and 2000 per hour at the peak of the shower.

3. RESULTS

The meteor outburst occurred between 1 and 2 hr UT on 1995 November 22 and was confirmed throughout Europe (Marsden 1995). The event was hard to miss, with visual observers counting five meteors per minute during the peak of the shower at 1:29.0 ± 0.6 UT.

Figure 1 shows the variation of meteor rates, which is a cross section of dust density through the meteoroid stream. Visual meteor rates are in terms of zenith hourly rates (ZHRs) (Jenniskens 1994) and are converted to particle number density for particles between 10^{-5} and 0.02 g (magnitude +7 to −1). Visual rates from meteor counts by our observers in Spain (*filled circles*) are compared to those from observers in the Czech Republic and Hungary with good agreement. Open circles are counts by J. Borovicka, P. Spurny, I. Teplickzy, and K. Hornoch (Borovicka & Spurny 1995; Znojil & Hornoch 1995). Radio MS rates are in arbitrary units, roughly the observed hourly rate, and they are scaled to the visual rates at the peak by a constant multiplication factor. Radio data from our observers in Finland and the Netherlands (*filled circles*) are compared to data from M. de Meyere in Belgium and K. Janos in Hungary (*open circles*), again with good agreement. The width of the meteoroid stream along the path of the Earth inferred from visually observed meteors is roughly one-tenth of the Earth-Moon distance and indistinguishable from the width derived from radio meteors. There is no strong spatial variation of particle sizes across the profile, although there is perhaps a slight excess of faint meteors at the beginning of the shower.

The particle brightness is a function of size, and the brightness distributions measured by various techniques are compiled in Figure 2. The ratio of stream and sporadic meteors is given as a function of magnitude, which eliminates the magnitude-dependent detection efficiencies of the techniques used. The sporadic meteor size distribution is exponential in this mass range, with an increase of a factor 3.4 in the number per magnitude bin (Kresáková 1966). In order of increasing sensitivity of the technique, the figure includes photographed meteors (*small filled circles*), visual counts (*crosses*), low–light-level TV imaging (*open square*), and radio meteor scatter counts. The latter are from measurements by I. Yrjölä and are for the 10 minute interval before 1:30 UT (*open circle*) and after 1:30 UT (*large filled circle*), respectively, which are nearly identical.

The α Monocerotid magnitude distribution shows no sign of a lower size cutoff down to the measured minimum particle mass of 10^{-5} g, or 0.3 mm diameter. On the other hand, there is a distinct cutoff for dust grain sizes above 6 mm (causing zero magnitude or brighter meteors), present in both the photographic and visual counts. Such a cutoff has not been seen before in the particle size distribution of annual meteor streams and must be considered a unique feature of this type of meteoroid debris.

In spite of the dearth of bright meteors, four α Monocerotids were photographed from two or more sites and seven were captured on video, which allow the calculation

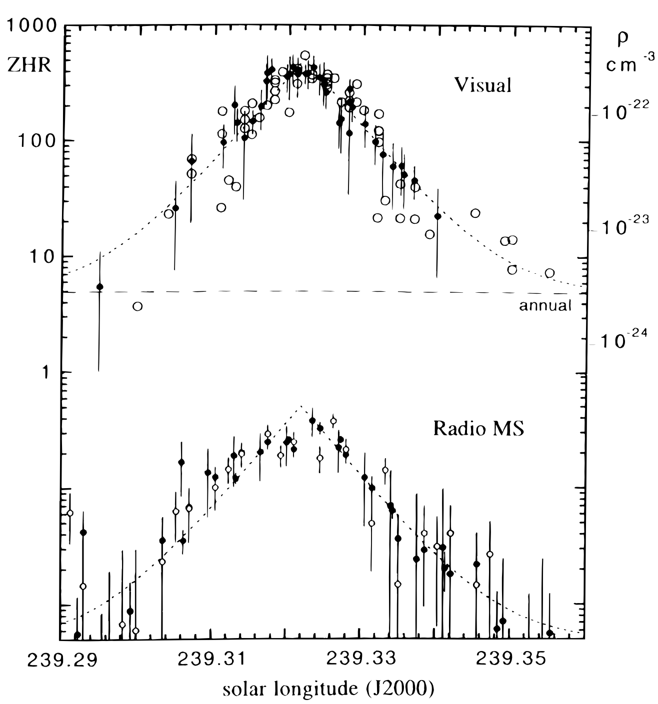

FIG. 1.—Variation of meteor rates along Earth's path

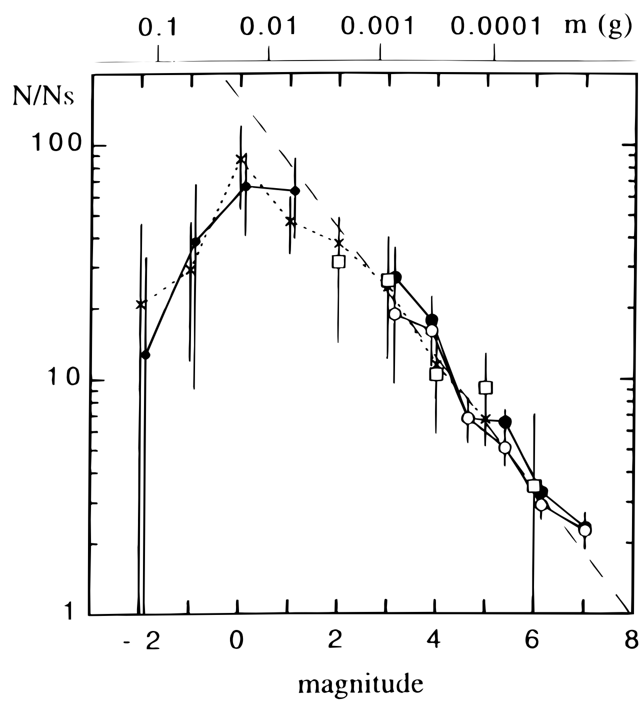

FIG. 2.—Dust particle size distribution in terms of the ratio of stream vs. sporadic meteors.

TABLE 1

OSCULATING ORBITAL ELEMENTS OF α MONOCEROTIDS AT THE EPOCH OF THE METEOR

Imaging[a]	Time (1995 Nov 22)	R.A.[b] (deg)	Decl.[b] (deg)	V_∞ (km s^{-1})	H_b (km)	H_e (km)	m_V (mag)	$M/C_D S$ (g cm^{-2})	$1/a$ (AU^{-1})	q (AU)	i[b] (deg)	ω[b] (deg)	Ω[b] (deg)
							Annual						
PH	3:57:41	117.53 ± 0.05	+1.18 ± 0.05	63.6 ± 0.4	97.5	84.1	−0.9	0.48	+0.013 ± 0.042	0.485	138.18	91.25	59.4252
							Outburst						
PH	1:41:21	117.13 ± 0.02	+0.99 ± 0.03	64.3 ± 0.5	110.8	81.3	−1.4	0.10	−0.036 ± 0.036	0.496	134.12	89.26	59.3295
	1:33:41	117.87 ± 0.13	+1.82 ± 0.15	65.1 ± 0.6	97.1	85.2	−0.4	~0.05	−0.062 ± 0.062	0.506	136.83	87.73	59.3242
	1:37:54	117.12 ± 0.13	+1.02 ± 0.15	64.4 ± 1.0	97.0	85.0	+0.2	0.05	−0.040 ± 0.099	0.499	134.33	88.91	59.3271
TV	1:41:51	118.09 ± 0.17	+0.38 ± 0.25	64.1 ± 0.6	116.9	99.2	+0	...	+0.015 ± 0.053	0.518	134.02	87.42	59.3299
	1:45:53	117.21 ± 0.11	+1.10 ± 0.28	64.3 ± 0.5	101.3	89.6	+1	...	−0.028 ± 0.048	0.495	134.48	89.48	59.3327
	1:29:40	117.19 ± 0.15	+1.15 ± 0.27	64.3 ± 0.3	103.1	95.7	+1	...	−0.028 ± 0.029	0.495	134.48	89.48	59.3213
	1:25:10	116.94 ± 0.17	+1.38 ± 0.25	63.9 ± 0.5	123.6	94.8	+2	...	+0.002 ± 0.045	0.481	134.31	91.52	59.3182
	1:37:39	117.10 ± 0.20	+1.26 ± 0.22	64.4 ± 0.3	112.4	89.1	+2	...	−0.042 ± 0.030	0.493	134.63	89.49	59.3269
	1:21:33	117.24 ± 0.13	+0.94 ± 0.27	63.1 ± 0.6	114.0	88.9	+3	...	+0.077 ± 0.055	0.480	133.38	92.71	59.3156
TV	1:31:14	116.89 ± 0.12	+1.30 ± 0.28	63.5 ± 0.7	...	97.0	+5	...	+0.037 ± 0.059	0.474	133.80	92.81	59.3224
							Parent						
		117.10 ± 0.13	+0.83 ± 0.16	64.0 ± 0.2					0.002 ± 0.019	0.488 ± 0.005	134.13 ± 0.34	90.66 ± 0.78	59.3220 ± 0.4

[a] PH = photographic, TV = television.
[b] Equinox J2000.

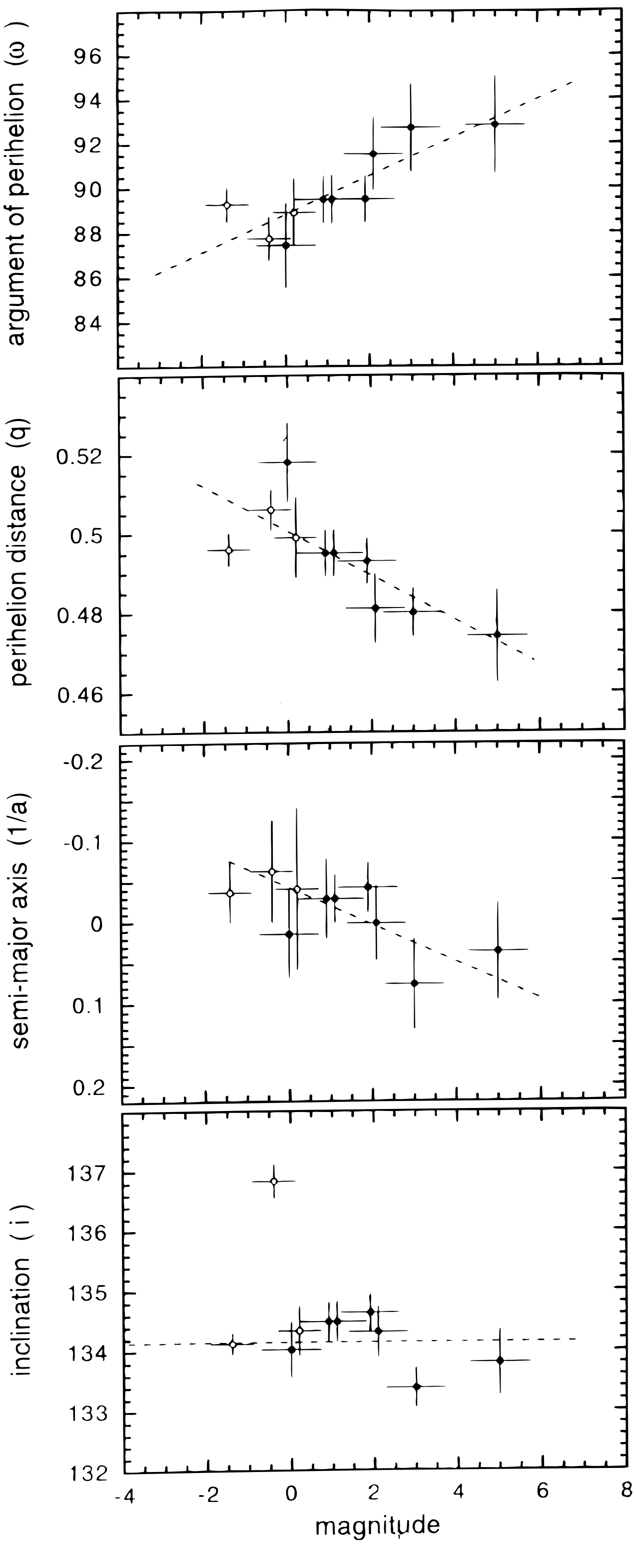

FIG. 3.—Osculating orbital elements as a function of meteor magnitude

of orbital elements through triangulation (Ceplecha, Boček, & Jezkova 1979; DeLignie & Jobse 1995). These orbits are given in Table 1, which lists the semimajor axis (a), perihelion distance (q), argument of perihelion (ω), and ascending node (Ω) of each particle. Also given are the beginning (H_b) and end height (H_e) of the recorded path of the meteor, the absolute visual magnitude for a distance of 100 km from the observer (m_V), and the mass over surface ratio $M/C_D S$, with C_D a dimensionless drag coefficient, calculated according to Halliday (Halliday 1988).

The orbits have a period $P > 140$ years (at the 98% certainty level), which definitely excludes the hypothesis that a clump of matter with a 10 year orbital period is responsible for the outbursts. The intrinsic spread in the radiant position is extremely small, with a standard deviation of less than 0°15 in position, which together with the short duration of the outburst proves the presence of a dust trail much narrower than the meteoroid debris responsible for the annual stream. Even so, the radiant is somewhat elongated along the ecliptic plane, suggesting that the dust is spread slightly more in the plane of the comet orbit than perpendicular to it. Note that only during the Draconid meteor storm of 1946 was a similar small radiant dispersion measured from single-station photographic records (Jacchia, Kopal, & Millman 1950) when Earth may have crossed the dust trail of the short-period comet P/Giacobini-Zinner (Kresák 1993).

The distribution of orbital elements of individual particles as a function of meteor magnitude is shown in Figure 3. It is found that there is a trend that particles of larger mass (i.e., brighter meteors) are in more eccentric orbits. Such particles also have a smaller argument of perihelion (ω) and larger perihelion distance (q) but similar inclination (i). Such variations have not been seen before and are unlike the effects of planetary perturbations on retrograde orbits (Kresák & Porubcan 1970), which implicates the ejection process.

The outburst meteors were relatively strongly decelerated in the atmosphere, indicative of a relatively low particle density. On the other hand, these meteors also ceased their path of light 5 km lower in the atmosphere than Perseid and Orionid meteors of the same brightness that enter the atmosphere at similar speed and entry angle. A conspicuous lack of flares also testifies to the unique character of the meteoroids in this stream. The lack of flares and the low penetration depth suggest that the meteoroids contained a relatively small fraction of materials of low melting point (Lebedinets 1985).

A final word concerns the annual α Monocerotid stream that is visible every year around November 22. From an assignment of meteors based on the newly determined radiant position, the annual α Monocerotid shower was found to have a peak visual meteor rate of only ZHR $= 5 \pm 1$ meteors per hour and an effective ($2 \times 1/e$) duration of about 3.5 days. The geometry of the orbit suggests that a second annual stream should be visible around May 20 with a radiant at R.A. = 351, Decl. = +18, $V_\infty = 62$ km s^{-1}, when the mean orbit passes 0.05 AU outside Earth's orbit at the descending node. If the width of the stream perpendicular to Earth's orbit is the same as in the path of Earth, then the expected meteor activity on May 20 will be no more than ZHR ~ 1.5.

4. DISCUSSION

While the presence of dust trails in the orbit of short-period comets has been demonstrated from *IRAS* data, there are no observations of dust trails in the orbit of long-period comets (Sykes et al. 1986; Sykes, Lien, & Walker 1990; Sykes & Walker 1992). Hence, by demonstrating that the α Monocerotid outburst is due to Earth traversing the trail of a long-period comet, we provide the first conclusive evidence of the presence of such trails.

Indeed, the meteoroid distribution in the α Monocerotid stream resembles known dust trails of short-period comets, except where we expect differences. Similar are the width of the stream and the shape of the stream cross section as well as the range of particle sizes (Sykes et al. 1990). The width of the stream reflects the mean ejection velocity, which is a function of perihelion distance and the size of the parent nucleus. Both are not necessarily different when comparing a long-period comet to the population of short-period comets.

On the other hand, the ejecta of long-period comets will spread much more rapidly along the comet orbit than the ejecta of short-period comets, thus spreading quickly the dust below the detection limit of *IRAS* (Sykes & Walker 1992). This is because even small ejection velocities, and radiation pressure differences, cause large variations in orbital period. The near-constant activity level of the stream in past outbursts (Jenniskens 1995a) is consistent with this spreading of dust along the comet orbit. Indeed, the observed peak spatial dust density in the α Monocerotid rail ($\rho_s = 2 \times 10^{-22}$ cm^{-3} for masses of 10^{-5} to 0.02 g) is 6 orders of magnitudes less than, for example, the peak density of the well studied P/Tempel-2 trail (Sykes et al. 1990). On the other hand, the total mass of dust in the α Monocerotid trail, assuming a circular cross section (Hughes & McBride 1989; Jenniskens 1994), is at least 6.10^{11} g, which compares to the 5.10^{13} g in the Tempel 2 dust trail (Sykes et al. 1990).

Models that address the infrared emission of the P/Tempel 2 dust trail suggest a lower size limit of $d \geq 1$ mm for particles trailing the comet and $d \geq 6$ mm for the forward portion of the trail (Sykes et al. 1990). It is thought that the smaller particles are expelled from the trail by solar radiation pressure. The α Monocerotid observations now allow, for the first time, a direct measurement of the particle size distribution in a dust trail. It is found that the distribution is relatively flat, with the number of α Monocerotids increasing by a factor of only 1.9 per magnitude bin (3.4 being the value for sporadic meteors). This confirms that a dust trail can be rich in relatively large meteoroids. On the other hand, there is no sign of a low-mass cutoff in the α Monocerotid trail, down to at least $d = 0.3$ mm.

A unique feature of the α Monocerotid trail is the upper limit in the size distribution. At first sight, this seems to reflect the largest particles that can be lifted off the nucleus. But that would suggest a very large ($d = 300$ km) comet nucleus (Whipple 1951). Alternatively, the observed mass dependence of orbital elements (Fig. 3) can be due to an increasing dispersion of ejection velocities for particles of smaller sizes. In that case, the upper limit in the particle size distribution results because all heavy particles with very small ejection velocities are ejected into hyperbolic orbits as a result of the radiation pressure (Kresák 1980), while some small particles are captured into bound elliptical orbits when their ejection velocity vector is sufficiently large and in the right direction.

5. IMPLICATION FOR THE SEARCH OF NEAR-EARTH COMETS

In the search for Earth-threatening planetesimals, the emphasis has been on objects that visit the inner solar system frequently enough to allow a detection from Earth (Morrison 1992; Scotti 1994). The population of long-period comets cannot be recorded fully in a reasonable search program. Unfortunately, long-period comets approach with little warning time from unusual directions, and while comprising only some 2%–10% of all potentially dangerous Earth impactors, there is evidence that they contribute a relatively high proportion to the very large (and most dangerous) impacts on Earth (Marsden & Steel 1994).

We have demonstrated now that it is possible to detect the presence of a long-period comet, and determine its orbit in space, while it still resides far from Earth and the body itself has not yet been detected. This is because the dust trail in the orbit of a long-period comet provides a detectable signature of its existence.

The importance of the present detection of the α Monocerotid dust trail, and from that the determination of an approximate orbit of the parent object, is in the fact that this will allow a directed search for the comet in that part of the orbit that would place it on a potential collision course with Earth. In this way, the warning time for an impact can, in principle be increased.

Our best estimate for the comet orbit is the mean orbit given in Table 1. This orbit was derived from the mean radiant and its error (excluding the extremes TV 1:21:33 and PH 1:33:41) and the mean preatmospheric entry velocity with an error as implied by the observed spread in $1/a$. The error given for the node of the mean orbit allows for a displacement of the trail with respect to the comet orbit. The exact location of the comet remains unknown because no historic record of the comet has yet been identified. Note that a possible association with comet 1944 I (Kresák 1958) can be excluded now.

A tentative estimate of the orbital period of the parent object can be made, assuming our hypothesis is correct that the particle size distribution cutoff at large masses reflects the semimajor axis of the parent body. The critical particle size is that for which the mean motion effects of radiation pressure and a negative relative ejection-velocity vector put the particle in a parabolic orbit. The semimajor axis of the comet orbit (a) can be found by equating the energy needed to eject a particle in a parabolic orbit at perihelion (q), were most ejection occurs, with the decrease of potential energy at infinity due to the effect of radiation pressure. Given that the ratio β of gravitational and radiation forces is $\beta = 1.14 \times 10^{-4} Q_{pr}/\rho d$, with Q_{pr} the radiation pressure efficiency factor (assumed to be unity), d the particle diameter in units of cm, and ρ the particle density in units of g cm^{-3} (Burns, Lamy, & Soter 1979), the equation becomes $a = q/2\beta$. For a mean density $\rho = 1$ g cm^{-3}, we find for the α Monocerotid parent comet $a = 1300$ AU or $P = 4 \times 10^4$ yr. For the same minimum mass, but with $\rho = 0.25$ g cm^{-3} as derived from the values of $M/C_D S$ of Table 2, we find $a = 500$ AU or $P = 1 \times 10^4$ yr.

Although the parent comet must have been beyond detectable range most of this century, we still can guess the size of the object and assess its impact hazard. The size of the nucleus can be estimated from the duration of the outburst and the spread in orbital elements for a given ejection model (Whipple 1951). The width of the dust trail is mainly a function of ejection velocity, while effects of radiation pressure and planetary perturbations can be neglected. From the width of the shower, we estimate the typical ejection velocity at perihelion at about 7 m s^{-1}. This estimate then puts the diameter of the object at 0.2–0.5 km.

In addition, it is possible to find the mass of the nucleus if we make the reasonable assumption that the meteoroid stream contains about half the mass of the comet before its first passage through the inner solar system, based on the argument that the comet loses mass quickly when it is still large during its first few returns to the inner solar system. (Hughes & McBride 1989). Most of this mass is now in the annual stream component, not in the dust trail. The total mass in the annual stream (Jenniskens 1994) is about 6×10^{14} g. This estimate puts the diameter of the object at 0.8 km, in good agreement.

A final estimate follows from the mass of the dust trail in comparison to mass estimates of dust trails of short-period comets. If the measured amount of dust is deposited in a small number of returns, it suggests again that the ejecta is from a relatively small ($d < 1$ km?) comet with intrinsic brightness $H = 9$–11 (Kresák & Kresáková 1987).

Still, such a relatively small object will release as much as 2×10^5 megaton of TNT (1×10^{21} J) of kinetic energy during a potential impact because the object would have a high preatmospheric geocentric velocity of 64 km s^{-1}.

Contrary to other known Earth-approaching objects, an impact from the α Monocerotid parent could happen in our lifetime because the planetary perturbations that direct the dust trail toward the Earth are not mass dependent. The chance of an actual encounter remains very small, however, because the comet can be anywhere in its orbit and the major planets would have to cooperate in directing the comet's parth in a collision course with Earth.

6. THE FREQUENCY OF FAR-COMET–TYPE METEOR OUTBURSTS

The potential zone near Earth's orbit that can be sampled for the debris of similar Earth-threatening long-period comets can be inferred from existing meteor stream models (Wu & Williams 1993). The location of the node of the meteoroids varies relative to Earth's orbit by up to ±0.01 AU in a manner reflecting the rotation of the Sun around the bary-center, the center of mass for the whole solar system (Jenniskens 1997). Indeed, the only two known comets associated with this type of outburst pass Earth's orbit to within ±0.006 AU, about twice the Earth-Moon distance (Table 2).

In the past century, at least seven long-period comets passed Earth's orbit within ±0.01 AU (Drummond 1981; Marsden & Williams 1992). The ones with the smallest orbital period are expected to have the highest flux densities because the matter is less diluted and a larger fraction of particles is ejected in elliptical orbits. Hence, instead of the typical 2–5 × 10^6 yr orbital period of "new" comets, the long-period comets that have detectable far-comet–type meteor outbursts probably have a period of typically 10^3 yr. Hence, there may exist some $7 \times 10^3/10^2 = 70$ detectable meteor streams that cause occasional outbursts of meteors.

Until now, only 14 such streams have been identified (Table 2). The level of annual activity is usually low, and in most years these streams may be all but dormant. Perhaps only once or twice every 60 years are the planetary positions favorable for a meteor outburst to occur (Jenniskens 1997). Only after 60 years will there be a repetition of the relative position of the important planets Jupiter (12 year orbital period) and Saturn (30 year). For that reason, there is not much information about these streams. Except for the Lyrids, α Monocerotids, and α Aurigids, most of these streams have been observed only once. No velocity measurements are available, hence the values given in Table 2 refer to an assumed parabolic orbit. Note also that the given radiant positions may be off by as much as 15°. Prior to our observations, the α Monocerotid radiant (117.1, +0.8) was placed at R.A. = 110, Decl. = −5 (Olivier 1936; Ducoty 1986).

Future observations of far-comet–type outbursts are needed. Not only do they provide unique information about the dust trails of long-period comets, and potentially the rate of mass loss in the form of dust from such objects, but they also provide important information about those long-period comets that threaten Earth. It is clear that a systematic search for meteor outbursts can help lower the potential danger to Earth from this population of comets and should be an integral part of any systematic search for near-Earth objects. We have demonstrated now that far-comet–type meteor outbursts can be observed successfully and the signature of earth-threatening long-period comets can be found, if a dedicated effort is made.

We thank the observers who participated in this project. Dutch observers at Alcudia-de-Guadix were Robert Haas,

TABLE 2

METEOR STREAMS WITH OCCASIONAL FAR-COMET–TYPE METEOR OUTBURSTS

Stream	Date	$\lambda_{\odot}^{max}$ [a]	R.A., Decl. (deg)	V_{∞} (km s^{-1})	B[b] (deg^{-1})	ZHR_{max}[b] (hr^{-1})	Comet	Δ[c] (AU)	P (yr)
Lyrids (Lyr)	Apr 22	32.1	271, +34	48	33	250	1861 I	+0.003	415
α Bootids[d] (aBo)	Apr 28	38.2	219, +19	23	37	...	...	...	...
α Circinids (aCi)	Jun 3	73.1	218, −70	∼28	80	>100	...	...	...
γ Delphinids (gDe)	Jun 11	80.4	312, +17	∼60	60	>200	...	...	...
κ Pavonids (kPa)	Jul 17	114.8	275, −67	∼25	30	60	...	...	...
β Perseids[d] (bPe)	Aug 7	135.4	52, +40	∼67	60	...	...	...	...
β Hydrusids (bHy)	Aug 16	143.8	23, −76	∼24	30	80	...	...	...
θ Aurigids (Aur)	Sep 1	158.7	94, +36	66	33	250	1911 II	−0.006	1900
ϵ Eridanids (eEr)	Sep 10	168.1	56, −14	∼57	10	>170	...	...	...
α Monocerotids (aMo)	Nov 22	239.3	117, +01	64	73	500	...	...	$\sim 1 \times 10^4$
o Orionids (oOr)	Nov 26	244.1	85, +04	∼45	30	140	...	...	...
α Lyncids (aLy)	Dec 20	268.8	138, +44	∼53	60	>350	...	...	...
α Centaurids (aCe)	Feb 7	319.2	210, −58	∼60	60	>230	...	...	...
α Pyxisids (aPx)	Mar 6	346.0	135, −35	∼28	>40	>50	...	...	...

[a] Equinox J2000.
[b] The meteor stream activity curve is described in terms of $ZHR = ZHR_{max}\, 10^{-B|\lambda_{\odot} - \lambda_{\odot}^{max}|}$.
[c] The minimum distance between comet orbit and Earth orbit.
[d] Shower of telescopic meteors.

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