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MINOR PLANET 2002 EX_{12} (=169P/NEAT) AND THE ALPHA CAPRICORNID SHOWER

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ABSTRACT

Minor planet 2002 EX_{12} (=comet 169P/NEAT) is identified as the parent body of the alpha Capricornid shower, based on a good agreement in the calculated and observed direction and speed of the approaching meteoroids for ejecta 4500–5000 years ago. The meteoroids that come to within 0.05 AU of Earth's orbit show the correct radiant position, radiant drift, approach speed, radiant dispersion, duration of activity, and distribution of dust at the other node, but meteoroids ejected 5000 years ago by previously proposed parent bodies do not. A more recent formation epoch is excluded because not enough dust would have evolved into Earth's path. The total mass of the stream is about 9×10^{13} kg, similar to that of the remaining comet. Release of so much matter in a short period of time implies a major disruption of the comet at that time. The bulk of this matter still passes inside Earth's orbit, but will cross Earth's orbit 300 years from now. As a result, the alpha Capricornids are expected to become a major annual shower in 2220–2420 A.D., stronger than any current annual shower.

Key words: comets: individual (169P/NEAT) – meteorites, meteors, meteoroids – minor planets, asteroids: general

1. INTRODUCTION

Until recently, none of the proposed parent bodies of the alpha Capricornid shower (IAU no. 1) fit the bill well (Table 1). Kramer (1953) first proposed that the shower originated from the poorly observed historic comet C/1457 L_1. Instead, Bernard et al. (1954) advocated that comet 72P/Denning–Fujikwawa was responsible, following a speculation by Denning (1920). Later, Sekanina (1976) assigned asteroids 2101 Adonis (1936 CA) and 9162 Kwiila (1987 OA) to the alpha Capricornids. Hasegawa (2001) grouped the photographed meteors from the general direction of Capricorn in July and August into 10 possible meteor showers, each of which was assigned to one of the previously proposed parent bodies, or bodies yet undiscovered. The alpha Capricornids were assigned to the 1785, 1878, and 1838 A.D. ejecta of 45P/Honda-Mrkos-Pajdušáková, based on the shape and orientation of the orbit of the comet in those returns. Instead, Wright et al. (1956) proposed that 45P/Honda-Mrkos-Pajdušáková might be the parent of another shower, now called the August Capricornids (IAU no. 199).

The first dynamical study of the origin of the alpha Capricornids was that by Neslusan (1999), who found an alpha-Capricornid-like shower from dust evolved from comet 14P/Wolf. However, 14P/Wolf was never close to Earth's orbit, and nearest at $q \sim 1.6$ AU only in between dramatic encounters with Jupiter in the period 1875–1922 A.D. Although Jupiter can evolve dust trailets into Earth's path, comets that are thus strongly perturbed by Jupiter cannot create a strong annual shower such as the alpha Capricornids, which has been seen for over a century. This was demonstrated numerically in the case of 7P/Pons-Winnecke by Vaubaillon (2004).

In the absence of close encounters, the main feature of the secular orbital evolution of Jupiter Family comets is a slow rotation of the nodal line, called a nutation cycle (Jenniskens 2006, 2008; Williams 2009). By rotating the nodal line of the current parent body orbit until intersection with Earth's orbit, a first-order comparison can be made between the observed orbital elements of the alpha Capricornids and those expected from the debris of a proposed parent body (Table 1). None of the previously proposed parent bodies listed in Table 1 have orbital elements in good agreement with those of the alpha Capricornids. Most importantly, in only two cases the orientation of the apside line is in agreement with that of the alpha Capricornids and in all cases the semimajor axis is either too long or too short.

Here, we investigate the new claims that minor planet 2002 EX_{12} is the parent body of the alpha Capricornid shower (Figure 1). Wiegert & Brown (2004) noted that the orbit of 2002 EX_{12} had an excess of meteoroid orbits near its vicinity from the alpha Capricornid shower. They were skeptical that the parent body had been identified, however, because based on the de-biased Near-Earth Object (NEO) distribution determined by Bottke et al. (2002), they calculated that sufficient number of asteroids existed in this orbital element regime for one in three chances that another asteroid provided a better match than 2002 EX_{12}. This pessimistic conclusion will be investigated below.

In late 2004, Jenniskens (2006, ch. 24) found independently that 2002 EX_{12} lagged the currently encountered alpha Capricornid meteoroids by only 300 years in the 4000–5000 year nutation cycle (Figure 2). This made 2002 EX_{12} a likely parent, because the alpha Capricornid stream was found to be relatively young based on its narrow dispersion of nodes perpendicular to Earth's orbit *at the other (ascending) node*. If the parent body still existed, it had to be nearby in terms of dynamical evolution. The (minimum) age of the stream was proposed as the time when the descending node of 2002 EX_{12} was last near Earth's orbit, at the time found to be around 10 A.D.—but now calculated at 70 A.D. (Figure 2).

Shortly thereafter, 2002 EX_{12} was discovered to be a weakly active comet near perihelion. Upon approach to perihelion in 2005, B. D. Warner at the Palmer Divide Observatory, Colorado, first detected a faint tail on July 28 and 29 (Warner & Fitzsimmons 2005). At the time, the comet was 0.19 AU from Earth and 1.1 AU from the Sun, just a week away from the closest approach to the Earth (0.147 AU on August 7) and due at perihelion on 2005 September 17 at a distance of 0.6 AU from the Sun. Fitzsimmons confirmed the tail on images taken on July

Table 1
Proposed Parent Bodies for the Alpha Capricornids

Body	λ_o (deg)	R.A. (deg)	Decl. (deg)	Vg (km s^{-1})	a^a (AU)	q (AU)	i (deg)	Π (deg)	Dist. (AU)
Alpha Capricornids	127.8	306.3	−9.1	22.2	2.618	0.602	7.68	35.57	0.000
169P/NEAT (2002 EX_{12})	128.8	306.6	−8.4	22.2	2.604	0.605	7.62	34.74	0.143
Previously proposed candidate parent bodies									
C/1457 L_1	132.2	293.9	−14.5	21.6	Inf.	0.770	4.17	11.05	0.105
72P/Denning-Fujikwawa	135.0	299.6	−21.7	18.5	4.328	0.780	8.53	15.89	0.152
45P/Honda-Mrkos-Pajd.	142.0	324.5	−10.9	24.7	3.023	0.530	2.56	55.15	0.060
141P/Machholz 2	149.1	318.5	−19.1	18.0	3.013	0.753	1.57	35.27	0.223
2101 Adonis (1936 CA)	105.4	295.3	−22.0	24.8	1.874	0.443	0.57	33.08	0.021
9162 Kwiila (1987 OA)	141.7	322.6	−2.8	18.0	1.497	0.606	7.04	56.13	0.097

Note. [a] Orbital elements for meteoroid that would intersect Earth's orbit (J2000). "Dist." is current miss–distance of the comet orbit.

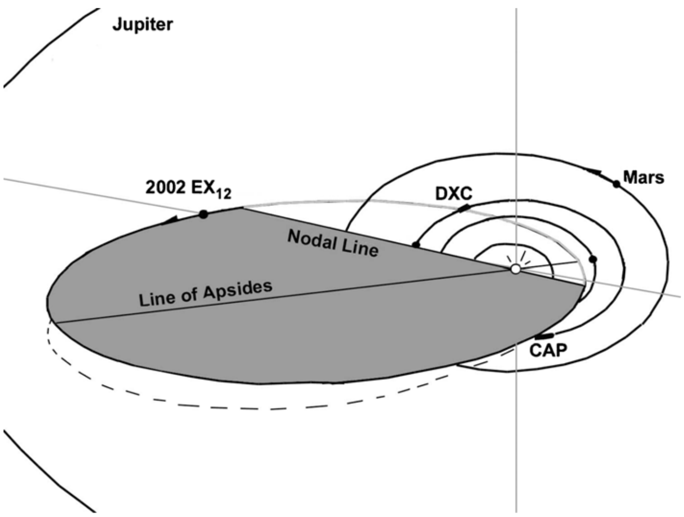

Figure 1. Orbit and location of 2002 EX_{12} at the time of discovery on 2002 March 15. The part in Earth's orbit is marked where alpha Capricornids (CAP) and Daytime chi Capricornids (DXC) are encountered.

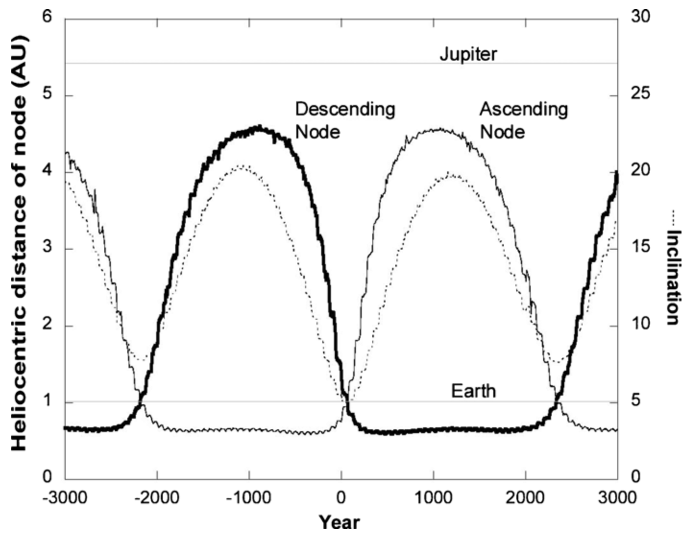

Figure 2. Nutation of the orbit of 2002 EX_{12} in the past 5000 years. Non-gravitational forces are ignored. The two solid lines are the heliocentric distance of the ascending and descending nodes as a function of time, while the dashed line shows the inclination of the comet orbit.

29, using the 2.0 m Faulkes Telescope at Haleakala, adding that no such tail was present in images taken on May 10 and 14. The extended emission faded at the end of October that year. Now re-designated 169P/NEAT (Green 2005), Warner (2006) determined a rotation period of 8.369 hr. Recently, DeMeo & Binzel (2008) measured the reflection spectrum of 169P/NEAT and found it similar to that of D-type asteroids.

In this paper, we study the orbital evolution of dust ejected from 2002 EX_{12} at different times in the past to investigate how this dust would appear today for an Earth-based observer. Results are compared to the distribution of the observed alpha Capricornid meteoroid orbits derived from a newly released video meteoroid orbit survey.

2. THE ALPHA CAPRICORNID SHOWER

2.1. Previous Observations

Activity from the constellation of Capricorn was first seen in 1871 by Prof. N. de Konkoly from O'Gyalla in Hungary (in present day Slovak Republic, Tass 1921) and coworkers at Agram, Schemnitz, Hodmezövásárhely, and Szathmárnémithi (de Konkoly 1880). From observations on July 28 and 29, de Konkoly determined a radiant at R.A. $= 307^{\circ}.2$, decl. $= -3^{\circ}.0$ (J2000). In 1873, he saw six meteors from a radiant at R.A. $= 314^{\circ}.3$, decl. $= -7^{\circ}.6$ on July 25 and 26, and five meteors from R.A. $= 318^{\circ}.3$, decl. $= -9^{\circ}.7$ on July 28. Later that century, Denning (1893) knew the Capricornids as an annual shower of slow and often bright meteors from the antihelion source direction. Visual observers continued to map the radiant and its daily movement (McIntosh 1935; Shigeno & Shigeno 2004), but the ecliptic low-inclination stream was established only with the publication of 12 multi-station photographic orbits from the Harvard Meteor Survey (Wright et al. 1956). Several of the Capricornids detected between July 16 and August 1 had similar orbits with inclination $\sim 8^{\circ}$, and this stream was called the alpha Capricornids.

A dearth of data has led to some confusion in recent years, with several authors finding other Capricornid showers in the same region and time frame. A second more diverse group in the August 8–22 time frame (August Capricornids, IAU no. 199) had lower inclinations, while a third group with a smaller semimajor axis was found active in late July. In the latest analysis of meteoroid orbits, Hasegawa (2001) identified 10 different showers, tentatively linked to seven corresponding parent bodies. These latter streams are more spurious. The alpha Capricornids, on the other hand, can be recognized by visual observers from mid-July until mid-August.

Jenniskens (1994) derived a peak zenith hourly rate of ZHR $= 2.2 \pm 0.3$ at solar longitude $121^{\circ}.7 \pm 0^{\circ}.9$, and an activity curve slope factor of $B = 0.041/^{\circ} \pm 0.007/^{\circ}$ from NAPO-MS visual

Table 2
Comparison of Model and Observations for Candidate 2002 EX_{12}

Parameter	Alpha Capricornids (IAU no. 1)			2002 EX_{12}	
	(1)	(2)	(3)	Main	Leading Cluster
λ_o (deg)	127 ± 1	127.7 ± 0.2	127.8 ± 0.4	127.1 ± 0.2	129.1 ± 0.4
R.A. (deg)[a]	307.0	306.8	306.26 ± 0.08	306.30 ± 0.03	308.07 ±0 .03
Decl. (deg)[a]	−8.0	−9.3	−9.05 ± 0.05	−8.90 ± 0.03	−8.69 ± 0.02
Vg (km s^{-1})[a]	22.2	23.4	22.20 ± 0.13	22.64 ± 0.01	23.21 ± 0.01
δR.A. (deg)[b]	2.6	2.7	0.93 ± 0.08	0.32 ± 0.03	0.42 ± 0.03
δDecl. (deg)[b]	1.5	1.3	0.57 ± 0.05	0.29 ± 0.03	0.26 ± 0.02
δVg (km s^{-1})[b]	1.5	1.7	1.02 ± 0.02	0.14 ± 0.01	0.18 ± 0.01
ΔR.A. (deg per deg)	+0.54	+0.91	+0.59 ± 0.05	+0.53 ± 0.02	+0.46 ± 0.02
ΔDecl. (deg per deg)	+0.25	+0.25	+0.26 ± 0.04	+0.27 ± 0.04	+0.26 ± 0.04
ΔVg (km s^{-1} per deg)	...	...	−0.16 ± 0.02	−0.20 ± 0.03	−0.24 ± 0.02
ZHR (hr^{-1})	9 ± 2	5.0 ± 0.2	...	...	...
FWHM (deg)	10 ± 1	15.4	10 ± 2	3 ± 1	5 ± 1
χ	2.0	2.31 ± 0.03	2.1 ± 0.3	...	...

Notes.
[a] For solar longitude λ_o = 127.8. (1) Jenniskens 1994, 2006; (2) Dubietis & Arlt 2004; Galligan & Baggaley 2002; (3) SonotaCo.
[b] Includes measurement error.

observations (Table 2). This translates to a duration FWHM = 15°.1 ± 2°.6. The shower was found active from July 19 to August 18. On closer inspection, however, more weight should have been given to the Dutch Meteor Society (DMS) observations reported in the same paper, derived by using plotted meteor tracks to verify association, from which we have a peak ZHR = 9 ± 2 hr^{-1} at λ_o = 127° ± 1° and a duration FWHM = 10° ± 1° (fitted Lorentzian profile), which agrees with the more abundant NAPO-MS data prior to λ_o = 121°, but not with the more scattered data from later days. This new result is in better agreement with Dubietis & Arlt (2004) in time of the peak and peak rate, but implies a slightly narrower profile (Table 2).

Dubietis & Arlt (2004) concluded from an independent set of visual observations that the shower was active from about July 4 to August 14, peaking on July 31 (127°.7 ± 0°.2 solar longitude, J2000) at a peak zenith hourly rate of ZHR = 5.0 ± 0.2 meteors hr^{-1} of duration FWHM = 15°.4. They found a magnitude size distribution index χ = 2.31 ± 0.03, not unlike that of other annual showers. Others, too, have reported such peak rates (Bellot 1990; Trigo 1991; Zvolánková 1993).

2.2. NEW ORBITAL ELEMENTS

Recently, a new database of orbital elements was released which was obtained by the SonotaCo consortium (led by T. Kanamori of Tokyo) using multi-station video observations of Japanese amateur astronomers with automated meteor detection software (UFOCapture) and orbit determination software (UFOOrbit; Kanamori (SonotaCo) 2009). Due to the use of wide angle lenses, the apparent magnitude of the bulk of meteors is in the range +1 to −4 mag. At this brightness, the sporadic background is relatively weak and the alpha Capricornids stand out well (Figure 3).

Some caution is warranted when using these data, because the determination of radiant and speed was done in an automatic process and individual records were not checked by hand. The velocities were those measured for the average velocity of the luminous path and were not corrected for (unknown) deceleration by the atmosphere. Several records pertain to the same meteor observed by different stations, which were mistakenly not unified to one. Incorrectly combined data from multiple records of meteors that happened almost simultaneously, close to each other, may cause a spurious background of “sporadic” meteors (T. Kanamori 2009, private communication).

That said, for the first time, the alpha Capricornid shower radiant is detected and can be followed over time during the period 119°–137°.5 solar longitude (FWHM = 10°.3), with a rather sudden onset on July 21 and lasting until August 11, a slightly more restricted time period than derived from visual observations. Based on the apparent magnitudes given for −1 and brighter meteors (assuming all meteors brighter than that were sampled with the same efficiency), we find χ = 2.1 ± 0.3. Other pertinent information is summarized in Table 2 and compared to literature values. The daily drift of the radiant is shown in Figure 4, as well as the intrinsic dispersion around this daily drift. Most of that may be on account of measurement error.

3. THE PARENT BODY

Minor planet 2002 EX_{12} (Ticha et al. 2002) is an intrinsically large object with H_N = +15.3 (Yoshida 2009). This corresponds to a diameter of $D \sim 5.7$ km if the albedo is a typical 0.04 (Pravec & Harris 2007). It revolves around the Sun every 4.2 years in an 11°.3 inclined orbit (Figure 1) with a Tisserand invariant T_J = 2.89 typical of Jupiter Family comets. It moves out to $Q = 4.602$ AU, staying 0.8 AU inside of Jupiter’s orbit, which makes this a stable orbit. Activity is confined to the period around perihelion, where the comet brightness in 2005 was best described with H_o = +15.8 and falling off with heliocentric distance according to $\sim r^{-8.0}$ (Yoshida 2009). The comet is much weaker than that expected for a 5.7 km sized body. Active Jupiter Family comets of similar size have H_o = +5.4, 10 mag brighter. Indeed, the comet is thought to be a Methuselah among comets, fading into extinction (Ferrin 2007).

3.1. The Model

The model (Vaubaillon 2004; Vaubaillon et al. 2005; Jenniskens & Vaubaillon 2007) evolved a cloud of dust grains under planetary perturbations, which were ejected from the

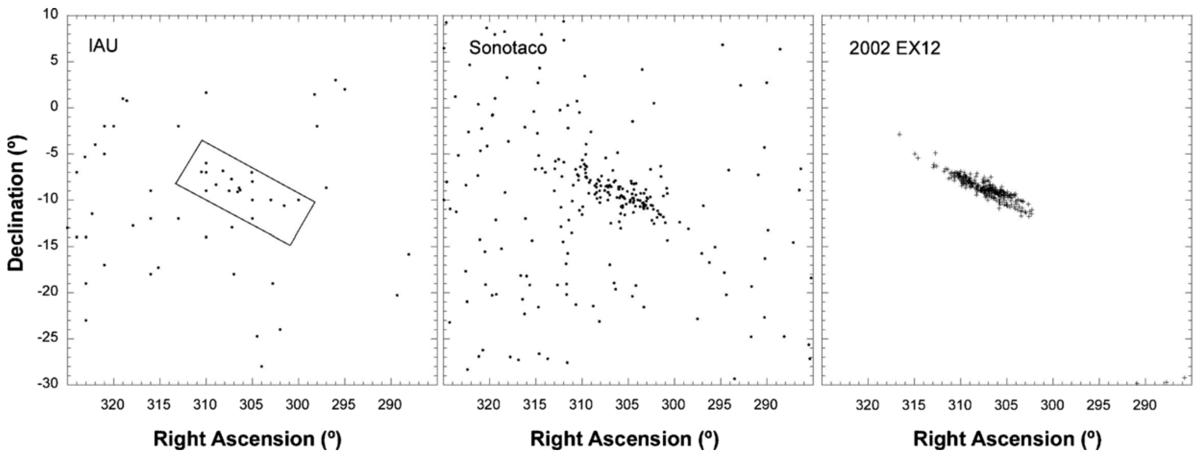

Figure 3. Radiant positions of July and August (solar longitude 100°–158°) meteors from the general direction of the alpha Capricornid radiant. Left: precise orbits in the IAU Meteor Orbit Database before 2009; middle: the new SonotaCo data; right: model results for 1–10 mm particles ejected from 2002 EX_{12} in 3000–0 B.C. that approach Earth's orbit to less than 0.05 AU (+, right) in 2000 A.D.

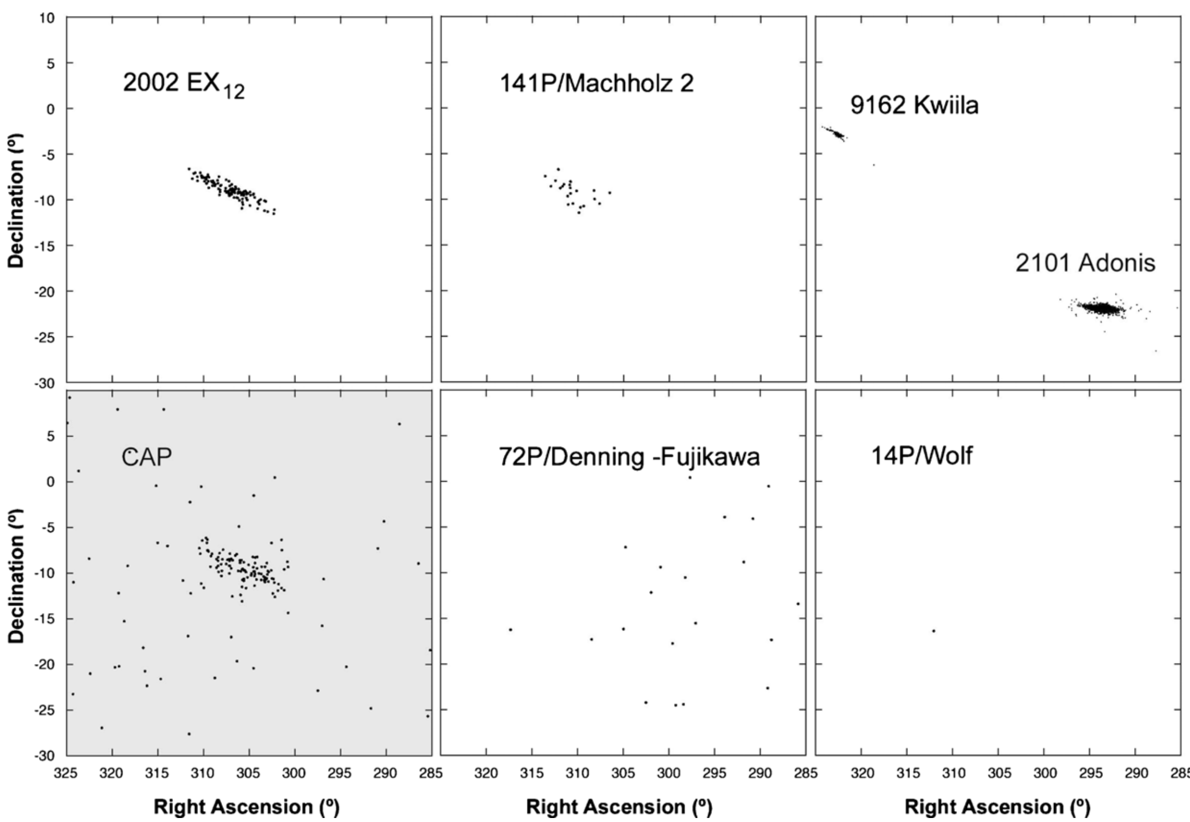

Figure 4. Radiant position for meteoroids less than 0.05 AU from Earth's orbit with solar longitude 115°–135°, for observed SonotaCo meteors ("CAP") and those calculated from 3000 B.C. ejecta by proposed candidate parent bodies. Meteoroids ejected by 2101 Adonis and 9162 Kwiila arrived outside the 115°–135° solar longitude interval.

comet at perihelion in 3000 B.C., 2500 B.C., ... etc. in 500 year intervals. The meteoroids were ejected according to the Crifo model for comet dust ejection (Crifo & Rodinov 1997), which is a slight adaptation of Whipple's comet ejection model (Whipple 1951), in a uniform manner in and out of the plane of the comet orbit on the sun-lit hemisphere.

The planetary perturbations are calculated for 10,000 particles each in three size bins (0.1–1 mm, 1–10 mm, and 10–100 mm). Assuming a density of 1 g cm^{-3}, the corresponding mean masses for each interval are 0.017 g, 17 g, and 17 kg and the corresponding visual magnitudes +6.7, −0.8, and −8.3, respectively (Jenniskens 2006, p. 594). The relevant size range for comparison to the observations is the middle 1–10 mm bin, while the other two bins represent the extremes of the known size distribution of alpha Capricornids and demonstrate the effects of grain size on the orbital evolution.

The meteoroids from each epoch of ejection were integrated forward in time until the current epoch (taken as 2000 A.D.). Subsequently, all those meteoroids were selected that passed to within 0.05 AU from Earth's orbit at the descending node, irrespective of the position in their orbit. The number of particles that did so in the 1–10 mm size bin was 120 (3000 B.C.), 86

(2500 B.C.), 14 (2000 B.C.), 19 (1500 B.C.), 24 (1000 B.C.), 20 (500 B.C.), and 11 (0 A.D.), respectively.

Only dust ejected around 0 A.D. or earlier has nodes at Earth's orbit in 2000 A.D. Any dust ejected more recently would not be seen as a meteor shower. Hence, if the alpha Capricornids were caused by a single fragmentation event, that event would have had to be prior to 500 A.D., in agreement with the (minimum) age estimated by Jenniskens (2006).

3.2. The Distribution of Radiants

In Figure 3, all model meteors are compared to those of observed shower meteors. The chosen meteoroid orbits were passing so close to Earth's orbit ($<$0.05 AU) that *the calculated radiant of each meteoroid orbit was nearly independent of the method used*. We used the method "H" of Neslusan et al. (1998), which involves changing the argument of perihelion to make the orbit intersect Earth's orbit. The dispersion of radiants calculated for ejection between 0 A.D. and 3000 B.C. does not vary significantly and all results are combined.

The dispersion of radiants is in excellent agreement with the observed distribution (Figure 3). In contrast, Figure 4 includes the distribution of radiants for other proposed parent bodies in Table 1. Again, we calculated back in time to 3000 B.C. the orbits of 14P/Wolf, 72P/Denning-Fujikawa, 45P/Honda-Mrkos-Pajdušáková, 141P/Machholz 2, 2101 Adonis, and 9162 Kwiila, then integrated the orbit of dust particles forward to 2000 A.D. We plotted the radiant of those meteoroids that passed in 2000 A.D. to within 0.05 AU from Earth's orbit at solar longitudes between 115° and 135°. None of these proposed parent bodies are in better agreement with the observed alpha Capricornids.

The best results were derived from 3000 B.C. ejecta by 141P/Machholz 2. Asher & Steel (1996) looked into the likelihood of meteors from this comet, but found that recent orbits stayed too far from Earth's orbit. Instead, we find that 3000 B.C. ejecta do arrive from the correct direction R.A. = 313.°0, decl. = −7.°8 with Vg $\sim$ 22.9 km s^{-1}, but are more dispersed and peak later (centered at solar longitude 135.°4). Jenniskens (2006) pointed out that it is perhaps possible that 2002 EX_{12} and 141P/Machholz 2 were split long ago.

No meteoroids met the required encounter conditions for 45P/Honda-Mrkos-Pajdušáková, 2101 Adonis, and 9162 Kwiila. 45P/Honda-Mrkos-Pajdušáková, like 72P/Denning-Fujikawa and 14P/Wolf, did not generate a compact annual shower from ejecta in 3000 B.C. Instead, all three comets could have contributed to the August Capricornids. Meteoroids ejected by 2101 Adonis did stay together (Figure 4), but arrive at Earth from R.A. = 293.°5, decl. = −22.°0 at Vg = 24.8 km s^{-1} during solar longitudes 92.°9–109.°3, before the alpha Capricornid activity period, while ejecta from 9162 Kwiila arrived later from R.A. = 322.°6, decl. = −2.°9 at Vg = 18.0 km s^{-1} during solar longitudes 135.°0–145.°0 (peaking at 141.°6).

3.3. Radiant Drift and Speed

Much of the spread in the right ascension of the observed alpha Capricornids is on account of the daily radiant drift. Figure 5 shows that drift for the direction (geocentric right ascension and declination) and magnitude (speed) of the approach vector. The observed drifts are in good agreement with the model predictions for ejecta from 2002 EX_{12}.

From the graph of R.A. and speed, it is clear that there are two strands to the model stream, one leading and one trailing strand.

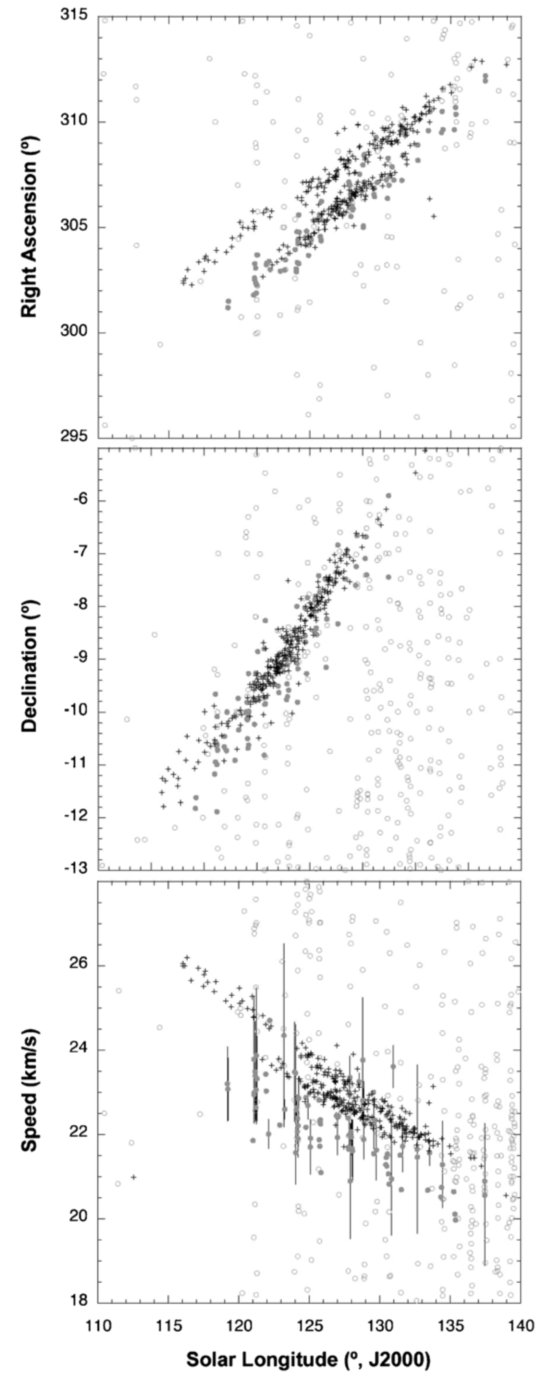

Figure 5. Drift of the geocentric radiant (R.A. and decl.) and geocentric speed (Vg) with solar longitude. Observed distributions (•, o) are compared to those calculated (+) from ejection of 1–10 mm particles by 2002 EX_{12} in 3000–0 B.C. that pass to within 0.05 AU in 2000 A.D.

The leading strand has higher R.A. at a given solar longitude, the same decl., and a higher geocentric speed. The number ratio of the two strands is not a function of epoch of duration, but does vary with the size of the meteoroids. The leading strand is absent in the smallest size bin.

The trailing strand is more compact and centered at the densest part of the observed alpha Capricornid shower. This is also where most theoretical radiants are for meteoroids that pass longer than 0.05 AU from Earth's orbit; hence we call this the "main strand." The leading strand is perhaps observed at the upper part where the density of solutions is highest.

We also report a strong drift in geocentric speed with solar longitude (Figure 5). This dependence on speed versus solar longitude is also in good agreement with the model prediction. The observed variation is -0.16 km s^{-1} per degree of solar longitude, while the model predicts an identical dependence. The absolute value of the speed is systematically underestimated by -0.8 ± 0.3 km s^{-1}, as would be expected if no account is made for deceleration of the meteoroid in the atmosphere.

To verify the model, results are compared to the precise photographic data obtained by Harvard in the 1950s and more recent data by DMS (Figure 6). These data are corrected for deceleration in the atmosphere. There is good agreement now between the measured and calculated radiant position and speed.

The model stream is more concentrated than the observed shower. The leading strand is also not as prominent (like the results for our [0.1–1] mm size bin, or the results for 0 A.D. in the [10–100] mm bin). The main strand has FWHM = $3^\circ \pm 1^\circ$, the leading strand has FWHM = $5^\circ \pm 1^\circ$ (peaking 2° later).

3.4. The Mass in the Stream

Now the distribution of the stream is known in three dimensions, we can calculate the total mass of the shower by including our measurement what fraction of meteoroids pass to within <0.05 AU. Earth only passes the outskirts of the stream. If the stream dates from 0 A.D., then this ratio is $11/10{,}000 = 0.0011 \pm 0.0003$. If the stream dates back to 3000 B.C., then the ratio is $120/10{,}000 = 0.012 \pm 0.001$.

For $\chi = 2.1$, the total mass is determined by the mass of the largest meteoroids. A zero-magnitude alpha Capricornid is about 8 g (Jenniskens 2006). Five meteors of -5 and two of -10 were reported in the SonotaCo data. DMS reports one -10 mag alpha Capricornid. We will set the limit at -10 mag, corresponding to 80 kg (Jenniskens 2006). Within 0.05 AU from Earth's orbit, the dust density does not significantly fall off. Assuming that the orbital period of the meteoroids is close to that of the parent body ($P = 4.20$ years), $\chi = 2.1$, ZHR = 5 hr^{-1}, $\langle \mathrm{Vg} \rangle = 22.2$ km s^{-1}, and a width of 10° in Earth's path, the total mass of meteoroids <80 kg that come to within 0.05 AU from Earth's orbit amounts to 1.07×10^{12} kg.

Combined with the previously determined fraction of meteoroids near Earth's orbit, we find that the total mass in the stream is 8.9×10^{13} kg if the meteoroids were ejected in 3000 B.C. On the other hand, if the meteoroids were ejected in 0 A.D., less would have evolved into orbits with a node near Earth's orbit and the total mass in the stream would have to be about 10 times higher (9.7×10^{14} kg).

4. DISCUSSION

The <0$^\circ\!.$5 agreement in angular elements, and <0.5 km s^{-1} agreement in speed, significantly narrows down the orbital element regime in which other potential parent bodies would need to exist. Based on the de-biased NEO distribution determined by Bottke et al. (2002), 3×10^{-5} of all NEO asteroids have similar a, e, and i as 2002 EX$_{12}$. With an estimated total of 61 ± 43 NEO Jupiter Family comets of $H < 18$ mag, the likelihood another parent body with similar agreement exists within that accuracy interval is calculated to be less than 1 in 300, or 1 in 33 when considering the total population of all NEO. This is a significant improvement from the previous odds of 1 in 3 calculated by Wiegert & Brown (2004).

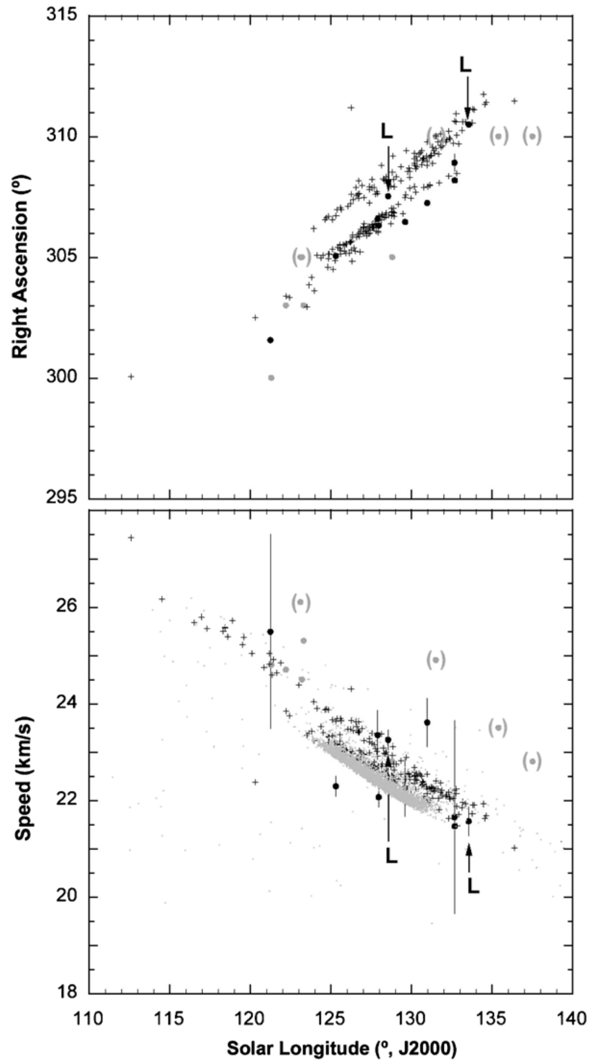

Figure 6. Same as Figure 5, for the most precisely measured photographic alpha Capricornids in the IAU meteor orbit database (data in box of Figure 3, left) and meteoroids in the 10–100 mm particle size range more typical of photographed alpha Capricornids. Gray points are from the precise Harvard orbits, dark points are Dutch Meteor Society measurements. Two possible leading-component meteoroids are marked "L." Small light gray dots show the calculated geocentric speed for particles passing further than 0.05 AU from Earth.

4.1. The Orbital Evolution

Now it has been demonstrated that the predicted stream is in good agreement with the observed shower, the origin and nature of the stream can be investigated. Figure 7 shows the distribution of meteoroids ejected in 0 A.D., as seen in 2000 A.D. The meteoroids have distributed all along the comet orbit and are found mainly at aphelion at any given moment of time. In three dimensions, the distribution of dust is warped by rotation around the line of apsides. The dispersion perpendicular to, and in, the ecliptic plane is smallest at perihelion. Near aphelion the radial dispersion is largest.

Figure 8 shows the descending node of the orbit of these meteoroids. The nodes are close to that of the comet itself, passing just inside Earth's orbit. Some orbits have evolved by rotating the node. The nodal line rotates in the direction shown by an arrow. Hence, some dispersion of the nodes has occurred in the forward direction of the nutation cycle, representing dust particles that nutate at a faster rate than the comet itself. Those

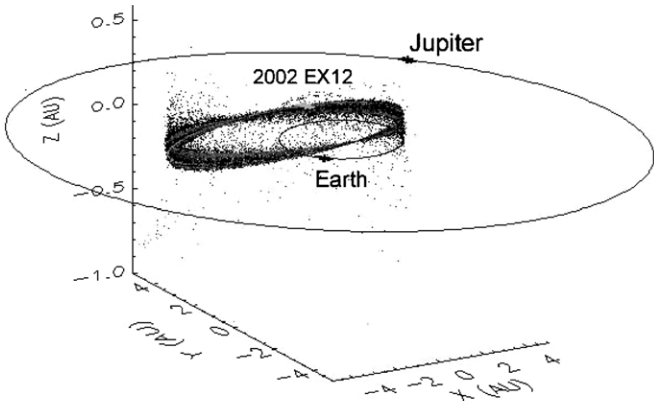

Figure 7. Distribution of meteoroids ejected in 0 B.C., as seen in 2000 A.D. in three dimensions. Most meteoroids are found near aphelion at any given time.

particles that are encountered by Earth are about 300 years ahead of the orbital evolution of 2002 EX_{12} itself (Figure 2).

One nutation cycle for 2002 EX_{12}, shown in Figure 2, takes 4500 years. The dashed line is the inclination, while solid lines show the heliocentric distance of the node. During one cycle, the inclination varies from 5° to 20°. The high-inclination phase corresponds to when one of the nodes is near Jupiter, as expected for an evolved orbit. The rotation of the nodal line is slow when the inclination is high and fast when the inclination is low, at which time the nodes move by Earth's orbit.

To speed up the nutation cycle, the orbit of the particles has to be slightly wider. Indeed, the model particles that pass within 0.05 AU from Earth's orbit have a slightly higher geocentric speed (Figure 6). The dust responsible for the alpha Capricornids represents dust that was either initially ejected in a wider orbit (due to ejection speed), or dust that evolved into slightly wider orbits due to planetary perturbations.

The initial ejection conditions are not likely responsible for putting the particles in those wider orbits. Radiation pressure and ejection speeds could do so, but then we would have expected smaller particles to evolve more rapidly than larger ones. Instead, the percentage of particles passing <0.05 AU from Earth's orbit does not change with size. It varied from 0.88% ± 0.09% to 1.21% ± 0.11%, and to 1.00% ± 0.10% for bin sizes [0.1–1], [1–10], and [10–100] mm, respectively. Hence, direct planetary perturbations are likely responsible for putting the particles in a wider orbit.

4.2. The Formation Epoch

The mass of 2002 EX_{12} is about 9.7×10^{13} kg (for density 1 g cm^{-3}). If the breakup occurred around 3000 B.C. or slightly earlier, then the remaining fragment is $\leqslant$52% of the original mass. We consider this a reasonable number, because it is in line with other streams thought to have been created by comet fragmentation (Jenniskens 2008). In those cases, too, we find that about as much mass is present in the stream than is left in the remaining comet.

If, instead, the comet broke as recently as 0 A.D., then the remaining fragment is only about 9% of the original mass. Although such a small remaining mass cannot be fully excluded, it is not in line with other known showers.

In other words, only after 4000 years does enough dust evolve into Earth's orbit to account for the observed alpha Capricornid rates.

This dust was not released in normal comet activity from water vapor drag (Whipple 1951), because normal active Jupiter Family comets would eject dust at a rate of only about 1000 kg s^{-1} for a period of 0.3 years around perihelion, which amounts to 1×10^{10} kg per orbit (Jenniskens 2006). In that case, enough dust would be released only after 8900 orbits, or about 37,000 years, rather than <5000 years suggested by the observations. Hence, a massive breakup is implied that occurred about 4000–5000 years ago.

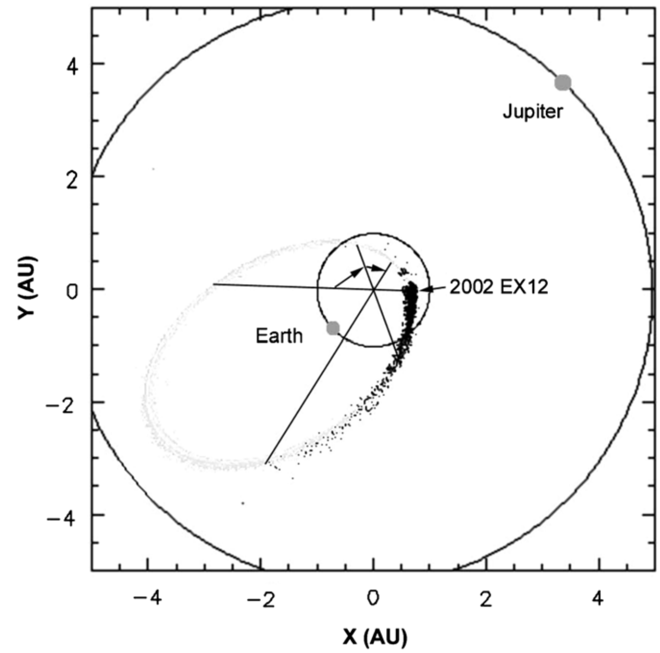

Figure 8. Same as Figure 7, now showing the distribution of the descending nodes. The node of 2002 EX_{12} is marked. The descending nodes are mostly close to that of the comet, just inside Earth's orbit, but some meteoroid orbits have evolved at a higher rate than the comet orbit itself and those meteoroids now have a node closer to Earth's orbit.

5. IMPLICATIONS

5.1. The Satellite Impact Hazard

According to our model, the alpha Capricornids have only gradually increased in activity since they first became visible in the late 1800s (Figure 9). In the next 300 years, however, the alpha Capricornids are likely to grow into a major annual shower when the nodes of the bulk of dust grains evolve into Earth's orbit. The predicted alpha Capricornid activity between 1800 and 2500 A.D. is shown in Figure 9. Rates are expected to stay around the current peak rate of ZHR = 5–9 hr^{-1} until about 2140 A.D., but will increase dramatically in the 23rd and 24th centuries to a peak of ZHR = 2200 hr^{-1} on an annual basis (assuming that the width of the shower does not change), half the visible shower peak rate during the 1999 Leonid storm.

At this rate, the shower can become a concern for satellite operators. ZHR = 2200 hr^{-1} translates to a peak particle flux of about 1.5×10^{-8} meteoroids larger than 10^{-6} g m^{-2} s^{-1}.

Much sooner, the meteoroid stream of 2002 EX_{12} will become a potential danger for space missions to Venus. At this moment, the nodes of most meteoroids cross the ecliptic plane near heliocentric distance R_h = 0.65 AU, just inside the orbit of Venus, and this heliocentric distance will gradually increase.

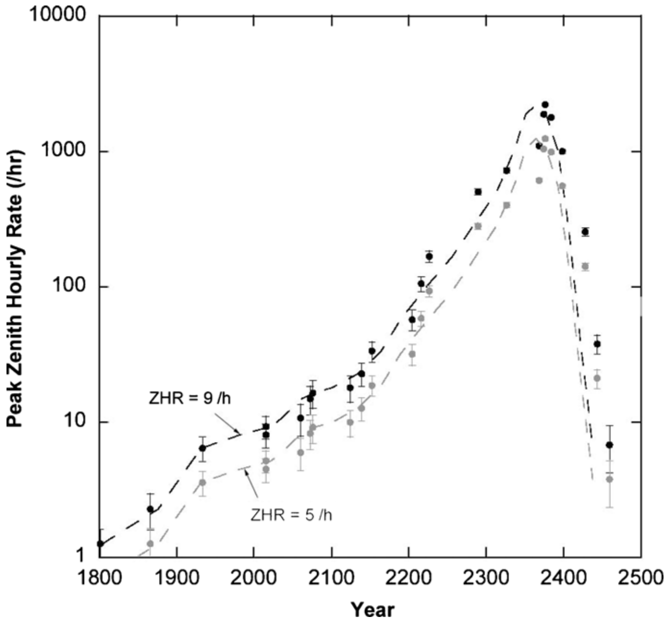

Figure 9. Expected time-dependent variation of the alpha Capricornid peak rate while the 3000 B.C. ejecta evolves from inside to outside Earth's orbit in the near future. A constant shower duration is assumed, and the result is given for two values of the present day peak zenith hourly rate. The equivalent year was calculated in two ways: by mapping to the node 2002 EX_{12} as a function of time (•) and from a third-order polynomial fit to the change in node of 2002 EX_{12} (dashed line).

5.2. *Fragmentation as a Mass-Loss Mechanism for Jupiter Family Comets*

At least 64 meteor showers are listed as established by the IAU Meteor Data Center (Jopek 2009), the first shower being the alpha Capricornids (IAU no. 1). Only 16 of those have active parent comets. Those that have are mostly of Halley and long-period type (Jenniskens 2006). The majority of short-period showers do not have an identified active Jupiter Family comet parent body.

Following the identification of asteroidal-looking minor planet 2003 EH_1 as the source of the Quadrantid shower (Jenniskens 2004), we searched for other such minor planets as potential sources of our short-period meteor showers. Jenniskens (2006, 2008) identified numerous candidates, most of which are (mostly) dormant Jupiter Family comets not yet fully decoupled from Jupiter, with a Tisserand invariant T_J below 3 and an aphelion just inside of Jupiter's orbit. Based on bias-corrected discovery statistics, Stuart & Binzel (2004) estimated that 30% ± 5% of the entire NEO population resides in cometary orbits having $T_J < 3$ (still under Jupiter's influence).

The source of these streams is thought to be periodic fragmentation instead of gradual outgassing (Jenniskens 2006). The meteoroid streams provide an important historical record of fragmentation and decay of these potential Earth impactors. Combined, these massive disruptions are capable of producing the bulk of the zodiacal dust cloud (Jenniskens 2006).

Much work is ahead to identify with certainty the source of the established short-period meteor showers, in order to evaluate statistically the rate of decay of the population as a whole. The present work adds one such stream, the meteoroids ejected by 2002 EX_{12}.

During the imminent return of the comet in January of 2010, 2002 EX_{12} is expected to brighten to a 10th magnitude object (15th magnitude if not active). This opportunity may be used to learn more about the physical properties of this object, in order to explain what drives the occasional massive disruptions.

5.3. *The Daytime Chi Capricornids*

The model predicts a brief daytime shower at the other node in January (Figure 1), with a radiant at R.A. = 309°.0, decl. = −29°.4, Vg = 22.7 km s^{-1}, peaking at solar longitude 303°.5 ± 0°.7 (J2000), with a width of 6°.4. The predicted peak ZHR = 2–5 hr^{-1}.

The alpha Capricornids (observed at the descending node) have an ascending node that is at higher heliocentric distance for increasing ascending node (Figure 10). The model does

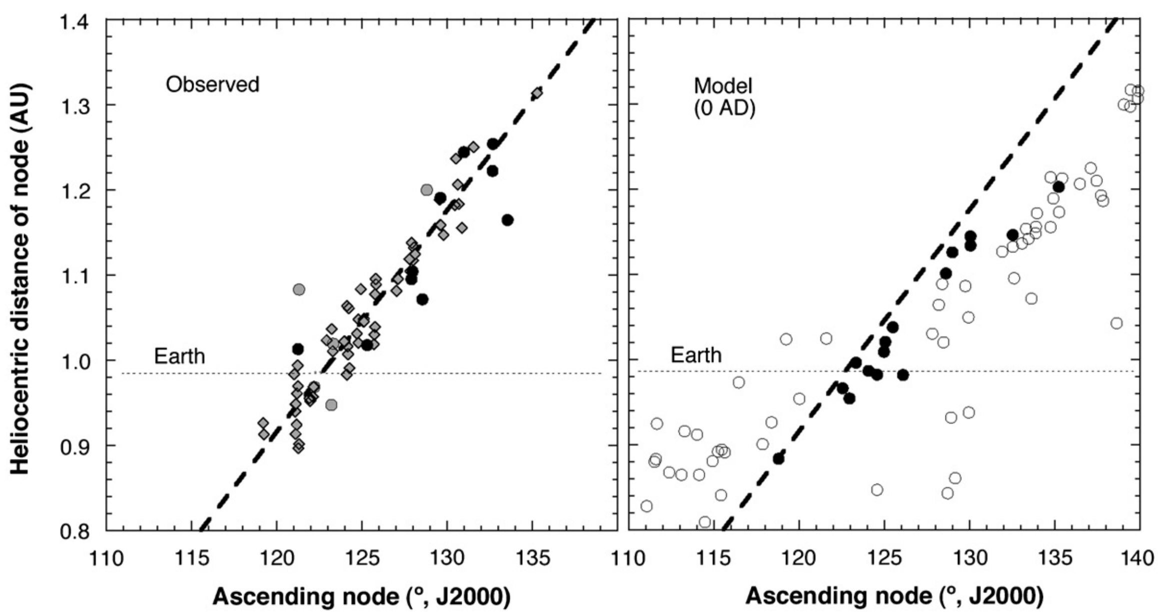

Figure 10. Heliocentric distance of the ascending node in January for alpha Capricornids observed in July and August. Observed data (left) are the nodes calculated for observed meteors ((•) DMS; (o) Harvard; (diamond) SonotaCo). Model data (for release of dust in 0 A.D.) show the node of all meteoroids in the model (o) compared to those meteoroids that have the descending node in Earth's path (+).

reproduce this effect, when considering only the meteoroids that have the descending node in Earth's path (+).

Until recently, the nearest identified shower from radar data are the Daytime Sagittariids-Capricronids (IAU no. 115), but those peak at solar longitude 312°.5 arriving at 26.8 km s^{-1} from R.A. = 315°.0, decl. = −23°.3. This shower is not caused by 2002 EX_{12}.

Now, Brown et al. (2009, 2010) report from a three-dimensional wavelet transform analysis of CMOR radar observations (Brown et al. 2008) that a shower of *Daytime chi Capricornids* (IAU no. 114) peaked at solar longitude 294 (ranging from 301° to 315°, or full width at half maximum about 6°), and arrived from R.A. = 304.7, decl. = −29.2, with Vg = 23.8 km s^{-1}, in good agreement. This implies that 2002 EX_{12} (=169P/NEAT) is also the parent of the Daytime chi Capricornids.

5.4. Physical Properties of the Comet and Meteoroids

Now the parent body has been identified, it is possible to study the alpha Capricornids in order to measure the comet's elemental composition. Borovicka & Weber (1999) have reported on a spectrum of an alpha Capricornid. They found that Na/Fe = 0.04, Mn/Fe = 0.003, Cr/Fe = 0.001, Mg/Fe = 3, and Ca/Fe = 0.001. This can be compared to the cosmochemical solar system abundances: Na/Fe = 0.07, Mn/Fe = 0.01, Cr/Fe = 0.015, Mg/Fe = 1.2, and Ca/Fe = 0.08 (Lodders 2003). The low calcium abundance was thought to be due to incomplete evaporation in the meteor, not a feature of the comet itself. Iron, too, may have been under represented by 30%, based on the volatile elements Na, Mn, and Cr. In that case, Mg may have been overabundant in 2002 EX_{12} by a factor of 3–8. Before drawing conclusions, however, more work along these lines is needed.

It is of interest to note that the alpha Capricornid and kappa Cygnid showers, both known for meteors rich in flares, have in common both age and the fact that Earth passes through outskirts of the stream (Jenniskens & Vaubaillon 2008). If initial ejection conditions (and radiation pressure) are not responsible for the meteoroids ending up in the outskirts of the stream, then processes such as space weathering over the formation timescale of the streams can perhaps explain the peculiar physical properties of the meteoroids.

6. CONCLUSIONS

Minor planet 2002 EX_{12} (comet 169P/NEAT) is the parent body of the alpha Capricornid shower (IAU no. 1) and the Daytime chi Capricornids (IAU no. 114), having had a massive breakup 4000–5000 years ago. The remaining comet is about half of the original mass. The observed alpha Capricornid shower represents only the outskirts of the dust complex. A small fraction of this dust evolved into longer orbits, which subsequently evolved faster along the nutation cycle to now have a node intersecting Earth's orbit and producing the observed alpha Capricornids. In the next 300 years, the bulk of the complex will evolve into orbits with a node close to the orbit of Venus, and then with a node close to Earth's orbit, making the alpha Capricornids a stronger shower than the current main annual showers in 2220–2420 A.D.

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Page 9

Q1

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