Ursids

Strong Ursid shower predicted for 2007 December 22

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The imminent return of comet 8P/Tuttle is expected to cause Ursid shower outbursts on December 22. There are occasional visual and forward meteor scatter observations of such outbursts from the previous perihelion return of 1994, and the one before that in 1980. In this paper, we investigated what may cause these outbursts and make predictions on what to expect from dust trails ejected in the period AD 300 – 1400. Younger trails do not contribute to these Filament-type outbursts. Our knowledge of the position of older trails suffers progressively from an uncertain position of the comet in its orbit. The comet passed close to Jupiter's orbit 15 000 years ago, at which time it may have been captured. We find that Jupiter's influence at the ascending node causes some meteoroids to evolve into resonant orbits that move into Earth's path. For 2007, we expect a strong shower with a peak ZHR = 40 – 80 per hour and a duration of FWHM = 2 – 8.5 hours, centered on December 22 at $20^{h}.0$ – $22^{h}.2$ UT (most likely $21^{h}.4$ – $22^{h}.2$ UT). Peak rates in 2008 – 2012 will be less. The exact peak time and duration, as well as structure in the shower profile, can identify the age of the stream. To find out, an airborne observing campaign is being prepared that would deploy from NASA Ames Research Center in California and would observe the 2007 December 22 Ursid shower over the Canadian arctic.

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1 Introduction

Comet 8P/Tuttle will return to perihelion on January 27, 2008, and has a favorable encounter with Earth, the best since the 1790 discovery, passing only at 0.25 AU on January 5. This could well be the brightest comet for 2008 and observing programs to study this comet are scheduled for the Hubble -, Spitzer -, and Chandra space telescopes, as well as from many ground-based observatories.

The Ursid meteor shower was discovered during an outburst in 1945, when the comet was at aphelion (Ceplecha, 1951). Another such outbursts occurred in 1986, and again in 2000. In most other years, this is only a minor shower with ZHR < 10.

The 2000 'aphelion' outburst was predicted (Jenniskens, 2000) and we now know that this dust is in the 6:7 mean-motion resonance with Jupiter, and in an orbit slightly longer than that of the comet (13:15), which, over time, causes a lag between the return of comet and the dust. It takes about 600 years for the dust to evolve inward to cross Earth's orbit, during which time the cloud of dust ended up lagging the comet by 600 times (13/15 x 7/6 -1) = 6.67 years, or half a typical 13.6-yr orbit (Jenniskens et al., 2002).

Occasional reports of high Ursid rates were also made in the years when the comet returned to perihelion during the previous two returns in 1980 and 1994. Jos Nijland of the Dutch Meteor Society observed an outburst in December 1982 (Veltman, 1983), and Japanese observers detected enhanced Ursid activity in

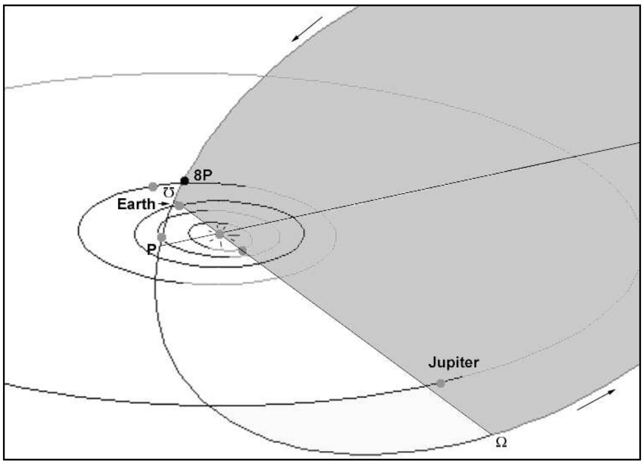

Figure 1 – The present orbit of 8P/Tuttle.

1994 (Ohtsuka et al., 1995). The high Ursid rate in 1994 was anticipated by Katsuhito Ohtsuka (1994), because he also had noticed high Ursid rates in 1981. Forward meteor scatter observations from Kuusankoski, Finland (Yrjölä & Jenniskens, 1998; Jenniskens et al., 2002), reproduced in Figure 2 (next page) demonstrated that the Ursids were in fact elevated in both 1993 and 1994 (Jenniskens, 2006). Significant activity was detected also in 1996, but not in 1995.

It is not clear at present what is responsible for these 'near-comet type' outbursts. 8P/Tuttle has a Halley-type orbit Tisserand invariant $T_J = 1.60$. Other Halley-type comets, such as 55P/Tempel-Tuttle and 109P/Swift-Tuttle, have similar outbursts of meteors when the comet returns to perihelion, called the 'Filament' component for historic reasons. Mean-motion resonances are suspected to play a role in the stability of this dust cloud. However, if they do, then the dust grains can get trapped in other resonances than the comet and the dust will tend to quickly spread along the whole orbit of 8P/Tuttle. It is not clear why these outbursts are seen only when the comet returns.

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To find out what mechanism is responsible, we studied the past evolution of 8P/Tuttle and its dust trails.

2 The orbit of 8P/Tuttle (15 000 BC – AD 2000)

The orbit of comet 8P/Tuttle (Figure 1) is only known with certainty since AD 1790, when the comet was first spotted by P. Méchain in Paris. However, the comet is rather large, with a diameter of about 15.6 km (Lamy et al., 2008; Snodgrass, 2007), based on the comet nucleus brightness at aphelion when the nucleus was bare. Hence, non-gravitational effects are relatively small and can be assumed constant in time with some justification.

We made predictions for the upcoming Ursid showers using two different models, that by Lyytinen (1999) and by Vaubaillon (2005a,b), each using a slightly different initial orbit for 8P/Tuttle and different integrators. Lyytinen started from the orbit listed in the Minor Planet Center's Catalogue of Cometary Orbits, 12th edition (1997), with slightly modified non-gravitational parameters to better match the 1790 observation of the comet, and his own design integrator to calculate the comet orbit back in time. Vaubaillon started from the most current orbit of comet 8P/Tuttle and its non-gravitational parameters (JPL K074/18), which was integrated backwards using the HORIZONS JPL program.

For the most recent returns, there is not much difference in the outcome. The comet has evolved close to the 6:7 and 7:8 mean-motion resonances with Jupiter, the first corresponding to a slightly longer orbital period than the comet, the second to a slightly shorter. In recent times, the comet has had an orbital period of about 13.687 years, at least since about 1400 AD.

Before that time, the solutions for different integration techniques and initial orbits start to deviate slightly. Starting with similar orbits for 8P/Tuttle, Lyytinen and Vaubaillon differed in perihelion time by less than 0.1 day in 1899, increasing to about 8 days in AD 980. Going further back in time caused this difference to increase rapidly, being almost a year in AD 774 and more than two years around AD 555. This is due to relatively close passages by Jupiter, at a distance of around 1 AU. These encounters are in part keeping the comet in resonance, but when these encounters are incorrectly calculated, then the orbital evolution will be off. The difference between these solutions mostly reflects the uncertainty in the comet orbit. Here, we consider dust trails ejected in the period 300 - 1400 AD.

For going further back in time, we adopted a different integration technique. The orbit of the comet was integrated back to 15 000 BC using a customized version of INPOP, the planetary ephemerides developed by Fienga et al. (2006). We find that the ascending node of the comet orbit was close to Jupiter around 13 000 BC (Figure 3).

At the present time, the descending node of the comet orbit is rapidly moving towards Earth orbit. Currently, the comet orbit passes about 0.095 AU outside of Earth orbit. In the next few hundred years, the node of the orbit will come only slightly closer, before moving outwards again.

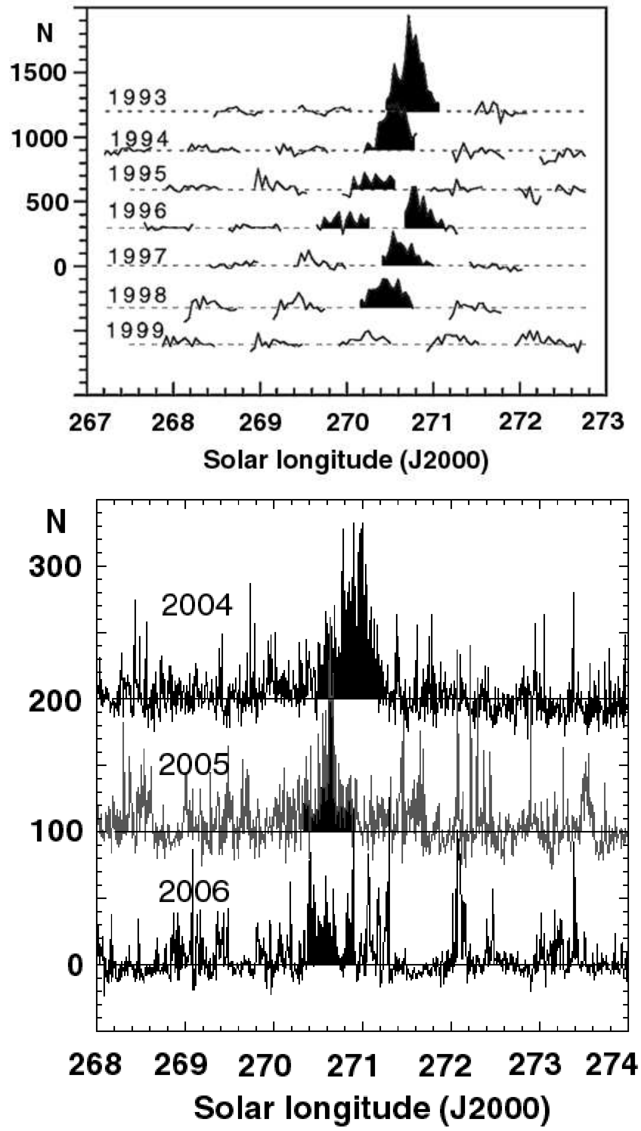

Figure 2 – Rate of meteors detected by forward meteor scatter from Kuusankoski, Finland, after subtracting the sporadic background. Counts have not been corrected for radiant elevation or instrumental geometry. The top graph is reproduced from (Jenniskens et al., 2002); black shaded areas are identified as enhanced rates that are likely due to the Ursid shower. The bottom graph shows more recent data (not on same scale).

3 The Lyytinen model

Based on the comet orbit, we generated dust particles at each perihelion between AD 307 and 788 and integrated the particles forward in time to the point of encounter with Earth orbit, following methods by Kondrat'eva and Reznikov (1985), McNaught and Asher (1999), and Lyytinen (1999). We have modeled the initial differences in orbit between comet and particle by changing the radiation pressure (ejection velocity being zero) and only positive radiation pressure test-particles are included.

Figure 4 shows how the dust moves in and out of Earth's path over time. Dust was near the Earth's or-

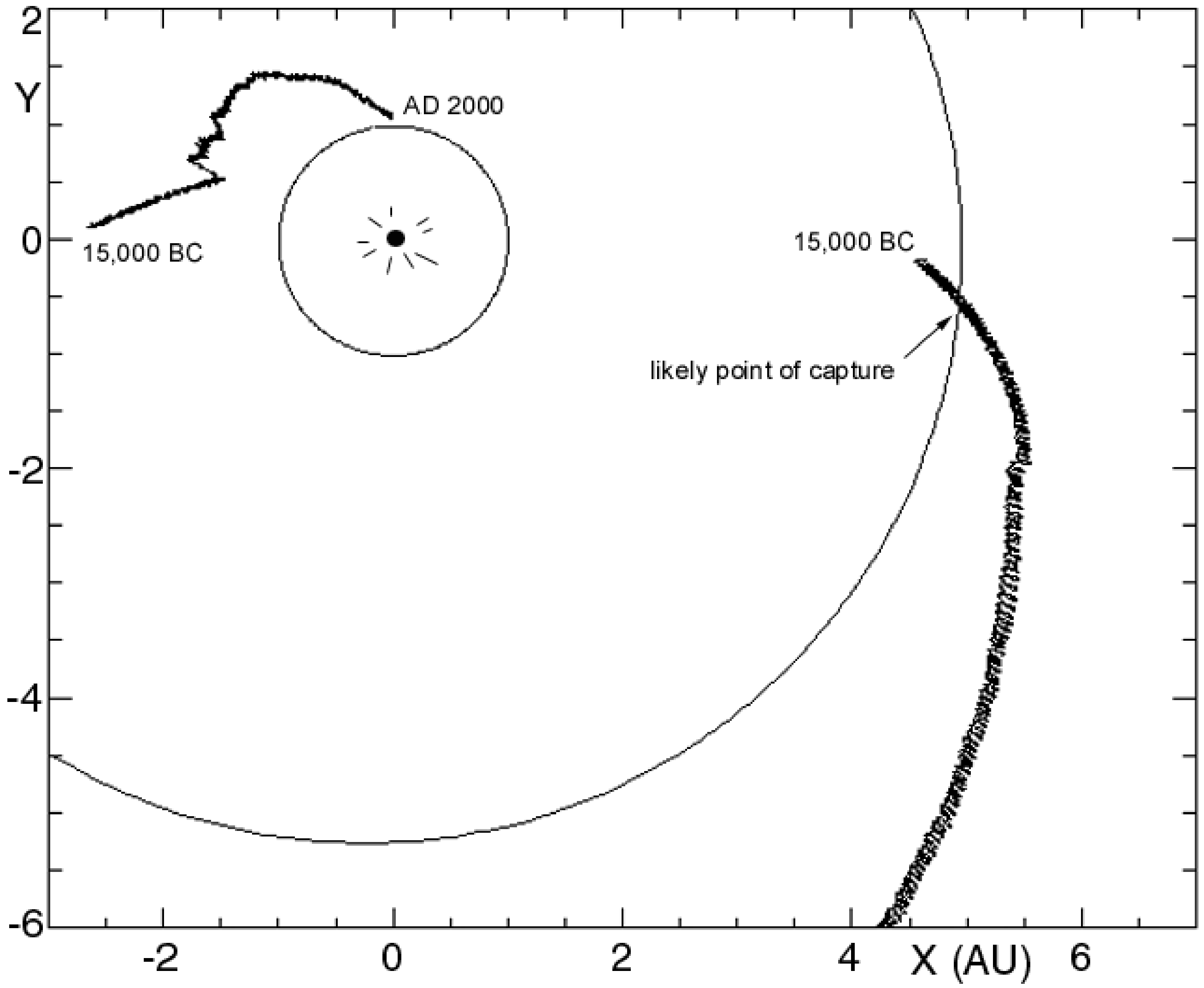

Figure 3 – The past long-term orbital evolution of 8P/Tuttle as indicated by the position of the ascending and descending node. The circles are the orbits of Earth and Jupiter. The curling lines are the calculated position of the nodes of the 8P/Tuttle orbit between 15 000 BC and AD 2000. The descending node is the one close to Earth orbit.

bit around the perihelion return in 1994 (and also that of 1980, not shown). We then calculated the anticipated dust trail encounters by counting those model particles that pass Earth orbit within 0.0015 AU at the time of the expected shower. Results are summarized in Table 1. All particles passing this point within 0.05 years are included.

If we investigate the dust density near Earth's path in the period 1993–1997, we see that much dust was near the Earth's path in 1993, 1994, and 1996, but not in 1995. This is in agreement with the radio forward meteor scatter data (Figure 2).

In later years, the commercial radio transmitters used in this experiment were shut down and other stations were used to make the counts (Figure 2, bottom diagram). As a result, the rates of recent years cannot be directly translated into a Zenith Hourly Rate, in the absence of a reliable scaling from visual ZHR estimates.

Based on the 1993 – 1997 Radio MS data and those from 2004 – 2006 (Figure 2), calibrated by scarce visual observations (Jenniskens, 2006, Table 5b; Jenniskens et al., 2006), the number of particles in the model was then multiplied by a factor of 1.10 to scale these counts to the peak ZHR values in Table 1.

The duration was calculated as the full spread of the particles in the model, keeping in mind that the actual spread is expected to be larger than calculated in absence of a variation in radiation pressure effects. All 1993–1997 outbursts had an FWHM (Full-Width-at-Half-Maximum) of about $0\overset{\circ}{.}35$ in solar longitude, or about 8.5 hours (Jenniskens et al., 2002). Our estimated durations in those years average 8.1 hours, in good agreement.

Based on these calculations, the upcoming Ursid shower encounter in 2007 would be quite promising, with a peak ZHR around 30–60. This estimate is uncertain by at least a factor of 3.6, judging from the standard deviation in the ratio between observed and calculated rates in the past. The outburst would have a duration of about FWHM = 4.9 hours (but perhaps as long as 8.5 hours if older trails are involved).

The meteoroids encountered in 2007 have beta values in the range 7.7×10^{-5} to 1.0×10^{-3}, with an average of 5.6×10^{-4}. These values for the radiation pressure

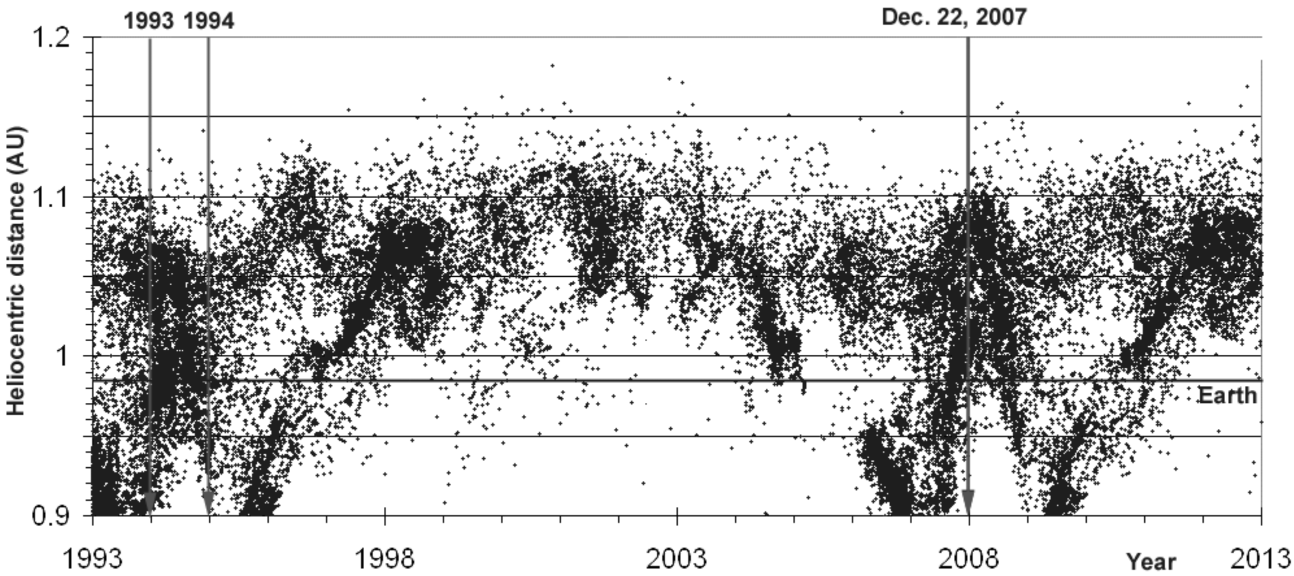

Figure 4 – Position of the node of the dust trails ejected in the period from AD 431 to 788 AD. The time of encounter of the Ursid meteors in Dec. 2007 is marked.

Table 1 – Calculated circumstances for the encounter with AD 307 – 788 dust trails of comet 8P/Tuttle, for all dust particles passing within 0.0015 AU from Earth orbit, according to the model by Lyytinen.

Year AD	Sol. Long. $\lambda_\odot$ (J2000)	Day	Time (UT)	FWHM (hr)	ZHR 413–788	ZHR 307–788	ZHR obs.
2008	270°60	Dec. 22	05^h07^m	9.7	23	30	future
2007	**270°57**	**Dec. 22**	$\mathbf{22^h08^m}$	**4.9**	**63**	**40**	**future**
2006	270°70	Dec. 22	19^h03^m	14.6	12	15	15 ± 5
2005	270°63	Dec. 22	11^h16^m	2.4	3	1	21 ± 6
2004	270°90	Dec. 22	11^h24^m	7.3	40	18	48 ± 6
1998	270°65	Dec. 22	16^h44^m	7.3	1	18	13 ± 3
1997	270°60	Dec. 22	09^h26^m	7.3	18	35	16 ± 4
1996	270°70	Dec. 22	05^h29^m	7.3	153	92	25 ± 5
1995	270°60	Dec. 22	21^h01^m	6.1	31	20	-.-
1994	270°75	Dec. 22	18^h21^m	9.7	67	62	50 ± 6
1993	270°96	Dec. 22	17^h03^m	11.0	78	95	100 ± 10
1983	270°95	Dec. 23	03^h24^m	7.3	8	32	-.-
1982	270°90	Dec. 22	20^h00^m	8.5	26	23	> 35
1981	270°90	Dec. 22	13^h53^m	9.7	17	39	55 ± 25
1980	270°90	Dec. 22	07^h40^m	7.3	111	156	-.-

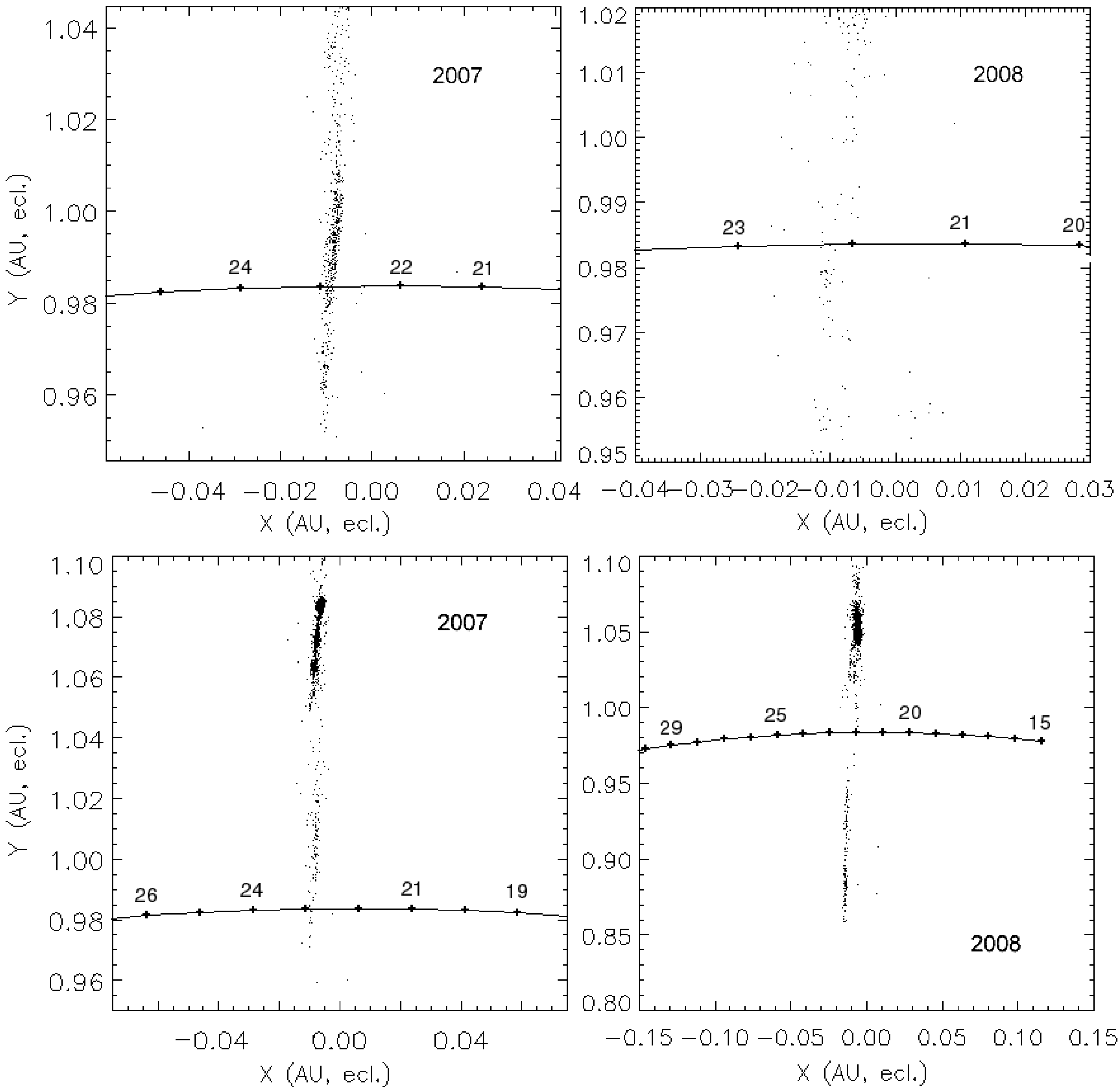

Figure 5 – Distribution of nodes of model particles ejected in AD 700 – 900 in the model by Vaubaillon, now projected on the ecliptic plane. The top diagrams are not merely enlargements of the bottom ones, but results from a second run of the model filled with more model particles.

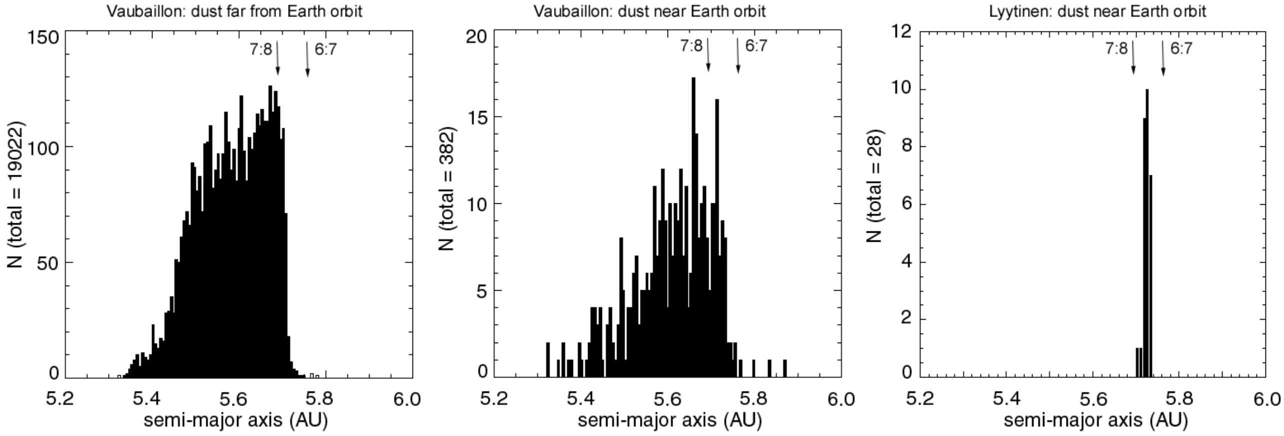

Figure 6 – Distribution of semi-major axis with mean-motion resonances marked. The two histograms to the right show particles that evolved into orbits close to the Earth's orbit, while the histogram to the left shows particles that did not.

are typical for large meteoroids seen as visual meteors, and do not need unusual shape or densities to meet Earth orbit. Past observations point to a high magnitude distribution index of $\chi \sim 2.6$ (Jenniskens, 2006), or a shower relatively rich in faint meteors. However, in 1996, the Ursid filament may have produced brighter meteors with $\chi = 1.9 \pm 0.3$ (Jenniskens et al., 2006).

The results in Table 1 are derived mostly from very few dust trails. The most significant contribution to the outburst in the period 413 – 788 AD comes from the 582 AD dust ejecta. Before AD 413, dust trails from AD 349, 362, 376, and 390 contributed dust in Earth's path. Table 1 shows our estimates of peak activity including or excluding the early trails. The exact perihelion dates are uncertain, so it is not clear at present if it is these dust trails that create the Ursid shower activity at Earth.

4 The Vaubaillon model

These calculations were repeated using the approach by Vaubaillon (2005a,b), wherein thousands of meteoroids are rigorously integrated using a massive parallel super computer at C.I.N.E.S., France. The initial conditions of ejection are based on the comet dust ejection model by Crifo and Rodinov (1997), which is not unlike that of Whipple (1951). Particles were ejected, initially, in the returns of AD 406, 611, 802, 1007, 1213, and 1392. The distribution of nodes in the ecliptic plane in 2007 and 2008 are shown in the bottom two graphs of Figure 5. A denser model of particles was created subsequently, considering all trails ejected in the period AD 700 – 900 (top graphs of Figure 5).

Most trails do not evolve into the Earth's path. We found that the dust trails of 745, 761, 775, 788, 802, and 816 contributed dust in the path of the Earth in 2007. The peak time or encounter of the AD 802 trail alone is calculated at about 2007 December 22, $18^{\rm h}48^{\rm m}$ UT. The combined dust trails from AD 700 to 900 shift that maximum to December 22, $20^{\rm h}03^{\rm m}$ UT (Table 2) or to $21^{\rm h}24^{\rm m}$ UT if a stronger restriction is made on which particles are counted. We consider this $21^{\rm h}24^{\rm m}$ UT time the more likely value.

The 700 – 900 trails alone concentrate along a thin filament in Earth's path, suggesting a brief FWHM = 2-hr shower. If older trails are involved, this could well be longer, up to the typical 8.5 hours. Hence, due to these small shifts in node, trails from individual years can cause substructure on the profile. The time of the peak and duration of the shower will measure the epoch of ejection.

5 The cause of Ursid outbursts

We suspect that some trails are efficient at producing grains that intersect the Earth's orbit, and others not, because Jupiter passes by the ascending node at the time when the comet did so as well soon after ejection of the meteoroids. The biggest numbers of particles are affected if Jupiter passes by when the dust is still close together in a short dust trail.

Changes in argument of perihelion and perihelion distance will have the biggest effect on moving the particle node inwards to the Earth's orbit. However, changes in semi-major axis may be more important in the long run due to the effect of mean-motion resonances.

That is because most 'close' encounters do not initially lower the perihelion distance. The closest encounters tend to increase q, rather than decrease it. It appears to be the somewhat more distant encounters, in the range 1.5 – 2 AU, that decrease the nodal distance in the long run. The initial perturbation may move the particles efficiently into the grasp of mean-motion resonances.

To examine the role of mean-motion resonances on the orbital evolution, we studied the semi-major axis of the particles that are near Earth's orbit in 2007 December. In the Lyytinen model, all particles close to the Earth's orbit have a narrow range in semi-major axis, not much different from that of the parent comet (Figure 6, right). The semi-major axis of these orbits is in between the nominal values for the 6:7 and 7:8 resonances with Jupiter's orbit, but to recognize the mean-motion resonance in the particle's evolution, one would have to examine the complete orbital evolution. We followed one of the test particles of the 582 trail and found it to lag the comet orbit by about one revolution, as expected for it being in the 6/7 resonance.

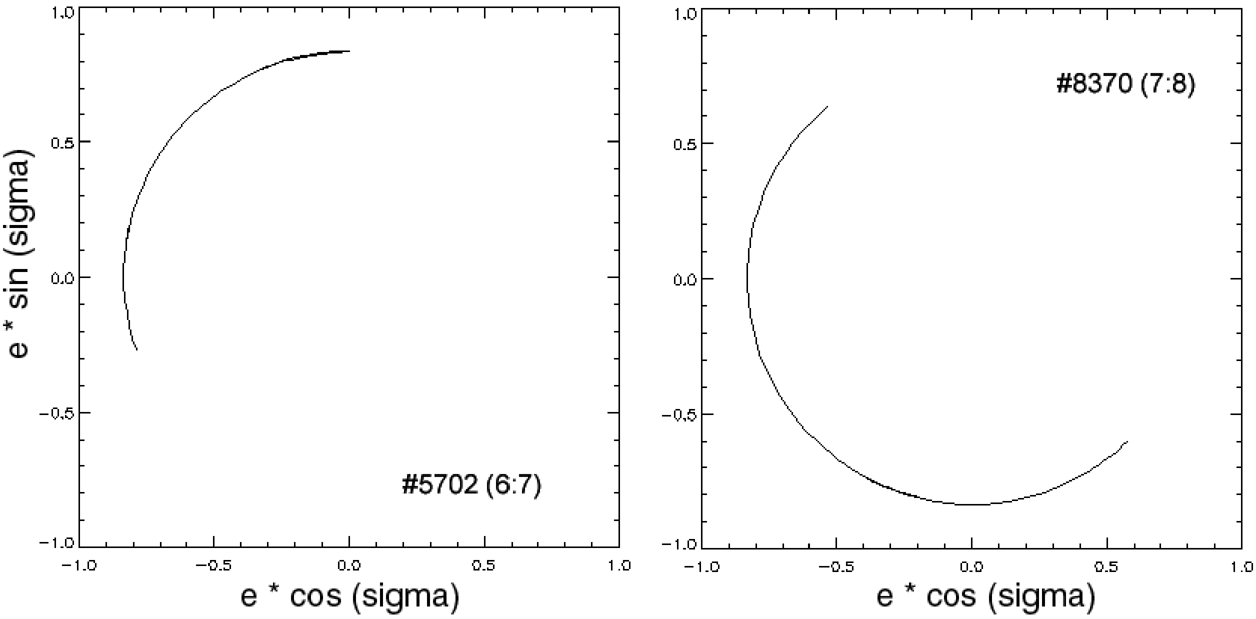

Figure 7 – Critical arguments for particle number 5702, moving in the 6:7 resonance, and particle number 8370, found to move in the 7:8 resonance.

Table 2 – Calculated circumstances for the encounter with AD 700 – 900 dust trails of comet 8P/Tuttle, for all dust particles passing within 0.002 AU from Earth orbit, according to the model by Vaubaillon.

Year AD	Sol. Long. $\lambda_\odot$ (J2000)	Day	Time (UT)	ZHR calc.	ZHR obs.
2012	270.49	Dec. 22	03^h01^m	15	(future)
2011	270.29	Dec. 22	16^h11^m	12	(future)
2010	270.42	Dec. 22	13^h02^m	23	(future)
2009	270.43	Dec. 22	07^h14^m	14	(future)
2008	270.48	Dec. 22	02^h18^m	20	(future)
2007	**270.48**	**Dec. 22**	$\mathbf{20^h03^m}$	**74**	**(upcoming)**
1999	270.44	Dec. 22	17^h54^m	14	-.-
1998	270.79	Dec. 22	19^h54^m	14	-.-
1997	270.48	Dec. 22	06^h33^m	13	16 ± 4
1996	270.54	Dec. 22	01^h44^m	22	25 ± 5
1995	270.62	Dec. 22	21^h28^m	14	-.-
1994	270.56	Dec. 22	13^h48^m	70	50 ± 6
1993	270.91	Dec. 22	15^h52^m	40	100 ± 10
1983	270.77	Dec. 22	23^h14^m	14	-.-
1982	270.94	Dec. 22	20^h54^m	58	>35
1981	270.80	Dec. 22	11^h36^m	23	55 ± 25
1980	270.80	Dec. 22	05^h24^m	25	-.-

In the model by Vaubaillon (Figure 6, left two graphs), we selected those particles that pass to within 0.02 AU, and compare the semi-major axis to those in the cloud further away. The adopted range of ejection speed and angle of ejection more efficiently moves particles into orbits that have 'close' encounters with Jupiter. The meteoroids found close to the Earth's path move in a range of orbits, although many are concentrated near the 7:8 and 6:7 mean-motion resonance. We see two spikes in the distribution that could correspond to these resonances.

We further demonstrated that the particles near the Earth are indeed moving in mean-motion resonances by calculating the critical arguments for a series of particles that pass near the Earth's orbit. Figure 7 shows how the critical arguments of particles number 5702 (in the 6:7 res.) and 8370 (7:8 res.) change over time. Resonances keep the orbital evolution from completing a full circle.

We can not yet be certain which trails contribute to the Filament outbursts, because that depends on the exact perihelion time of the comet in those years. The perihelion time determines the timing of close encounters with Jupiter.

Interestingly, it appears possible to infer from the peak time of the shower, and from substructure in the activity profile and the radiant distribution, which trails contribute to the Ursid outbursts. If so, the orbit of 8P/Tuttle could be reconstructed far into the past.

We can not exclude the possibility that the Filament component is much older than the 600 – 1,700 years considered in our model. In that case, the peak rate and time may be very different than predicted here. Dust could have been generated as far back as the time of capture in its current orbit by Jupiter. Careful observations of the Ursid shower may provide evidence when 8P/Tuttle was captured.

In our opinion, it is likely that 8P/Tuttle was captured during the most recent encounter of the comet node with Jupiter's orbit about 15 000 years ago. In some ways, comet 8P/Tuttle still looks fresh. Comet 8P/Tuttle spews out as much water vapor as does comet 1P/Halley, which is of nearly the same size as 8P/Tuttle. Comet Halley is thought to have been captured about 20 000 years ago (Jenniskens, 2006).

On the other hand, Tuttle is much less bright for a visual observer on the ground. That is because most of the dust is lost in the form of large dust grains (with sizes much larger than the 0.5 micron that efficiently scatters sunlight) that cause our Ursid meteor shower. Why is that?

How does the dust evolve from ejection to the point of being encountered by the Earth? It will be interesting to compare the meteoroid size distribution as measured in the shower and during ejection in the return of 8P/Tuttle in 2008. The meteor shower observations may help interpret the remote sensing observations of the comet and give new insight into the conditions of dust ejection. The meteor observations can also provide unique information on the main element composition of the comet dust. Conversely, a better understanding of the present day ejection conditions from remote sensing may provide new understanding of the origin and dynamical evolution of the meteoroid stream.

6 Conclusions

In December of 2007, we expect a strong Ursid shower with rates similar to that of a Perseid shower in summer for observers with clear sky and a radiant high in the sky. This will be the strongest outburst in this season's return of the comet to perihelion. The near full Moon will make this outburst hard to observe from the ground, especially because the shower might be relatively rich in faint meteors.

An airborne observing campaign is in preparation called the Ursid Multi-Instrument Aircraft Campaign, with the goal to deploy from NASA Ames Research Center in California and fly over the Canadian arctic at the predicted time of the shower. The mission is to measure the dust density in Earth path and, for the first time, accurately measure the spread of the dust in search of features that could still identify individual dust trails in the dust distribution. At altitude, the scattering of moonlight is less and, with a full-width-at-half maximum of about 5 hours, a 12-hour flight centered on 20^{h} UT is expected to cover most of the profile.

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References

Ceplecha Z. (1951). "Umids-Becvar's meteor stream.". *Bull. Astron. Inst. Czech.*, **2**, 156–159.

Crifo J. F. and Rodionov A. V. (1997). "The dependence of the circumnuclear coma structure on the properties of the nucleus". *Icarus*, **129**, 72–93.

Fienga A., Manche H., Laskar J., and Gastineau M. (2006). "Nomenclature, precession and new models in fundamental astronomy". In *26th meeting of the IAU, Joint Discussion 16, 22-23 August 2006, Prague, Czech Republic*, number 15 in JD16, page 2005.

Jenniskens P. (2000). "Ursid meteors 2000". IAU Circular 7547. ed. Green, D. W. E.

Jenniskens P. (2006). *Meteor Showers and their Parent Comets.* Cambridge University Press., Cambridge, U.K., 790 pages.

Jenniskens P., Lyytinen E., de Lignie M. C., Johannink C., Jobse K., Schievink R., Langbroek M., Koop M., Gural P., Wilson M. A., Yrjölä I., Suzuki K., Ogawa H., and de Groote P. (2002). "Dust trails of 8P/Tuttle and the unusual outbursts of the Ursid shower". *Icarus*, **159**, 197–209.

Jenniskens P., Nakano S., Ueda M., McBeath A., Vandeputte M., Lyytinen E., Yrjölä I., Moilanen J., and Brower J. (2006). "Ursid meteors 2006". IAU Central Bureau Electronic Telegrams CBET 788. ed. Green, D. W. E.

Kondrat'eva E. D. and Reznikov E. A. (1985). "Comet Tempel-Tuttle and the Leonid meteor swarm". *Solar Syst. Res.*, **19**, 96–101.

Lamy P. L., Toth I., Fernandez Y. R., and Weaver H. A. (2008). "JPL small body data browser". `http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=8P&orb=1` . To be published, posted on NASA JPL website.

Lyytinen E. (1999). "Leonid predictions for the years 1999–2007 with the satellite model of comets". *Meta Res. Bull.*, **8**, 33–40.

McNaught R. H. and Asher D. J. (1999). "Leonid dust trails and meteor storms". *WGN*, **27**, 85–102.

Ohtsuka K. (1994). "Expectation for enhancement of the Ursids activity in 1994". Technical Report 14, Tokyo Meteor Network Report, 85-87 pages.

Ohtsuka K., Shioi H., and Hidaka E. (1995). "Enhanced activity of the 1994 Ursids from Japan". *WGN*, **22**, 69–72.

Snodgrass C. (2007). *Forms and rotational states of the nuclei of ecliptic comets.* PhD thesis, Queen's University Belfast. Full text at http://homepage.mac.com/colinsnodgrass/FileSharing2.html.

Vaubaillon J., Colas F., and Jorda L. (2005a). "A new method to predict meteor showers. I. Description of the model". *Astron. Astrophys.*, **439**, 751–760.

Vaubaillon J., Colas F., and Jorda L. (2005b). "A new method to predict meteor showers. II. Application to Leonids". *Astron. Astrophys.*, **439**, 761–770.

Veltman R. (1983). "De herfst- and winterakties 1982". *Radiant, J. DMS*, **5**, 4–9.

Whipple F. L. (1951). "A comet model. II. Physical relations for comets and meteors". *Astrophys J.*, **113**, 464–474.

Yrjölä I. and Jenniskens P. (1998). "Meteor stream activity VI. A survey of annual meteor activity by means of forward meteor scattering". *Astron. Astrophys.*, **330**, 739–3752.