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ASTRONOMY AND ASTROPHYSICS

Meteor stream activity

IV. Meteor outbursts and the reflex motion of the Sun

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Abstract. A third meteor outburst of Aurigids was observed in 1994, similar to two previous events in 1935 and 1986. Again, the parent comet was far from perihelion. In search of a cause for these outbursts, the role of planetary perturbations was examined. It is found that the Aurigid outbursts, and other such outbursts, occur when the position of the planets Jupiter and Saturn are in two different configurations that are nearly equivalent in barycentric displacement of the Sun at the time of the outburst. It is proposed that the Sun's reflex motion is a (distorted) image of the displacement of a trail of dust relative to the Earth's orbit. It is found that existing numerical models of meteor stream formation feature this inferred motion of the stream. One implication is that future returns can now be anticipated with greater confidence.

Key words: meteors: meteoroids – comets: general

1. Introduction

For yet unknown reasons, some meteor streams soar into a spectacular display one year, while the next year rates are back to the normal low level of annual activity. The most intriguing examples are the Aurigids, Lyrids, and alpha-Monocerotids. These streams are associated with long period comets that were far from Earth at the time of the outbursts. It is still poorly understood what physical mechanism is responsible for these "far-comet type" meteor outbursts and the strong variation in rates from year to year, but the meteors are most likely from relatively fresh cometary ejecta of large cm-submm sized grains that have not yet diffused into the dust component that causes the annual meteor stream (e.g. Hughes 1982, Kresák 1993, Jenniskens 1994; 1995).

Although far-comet type outbursts do not occur in relation to the orbital period of the parent comet, outbursts do not manifest at random. The Lyrids, for example, were strong in 1803, possibly in 1863, in 1922, and in 1982, which forms a sequence of 60 year intervals or fractions thereof. By adding other accounts of possible outbursts of this stream, Guth (1947) inferred a period of 12 years and pointed out that in a majority of cases the planets Jupiter or Saturn were in conjunction with the stream at the time of the outburst. The alpha-Monocerotids were seen in 1925, 1935 and 1985, which suggests a ten year periodicity. Until now only two outbursts of Aurigids have been observed.

Guth suggested that the Lyrid maxima are some kind of resonance nodes on the comet's orbit, where occasional encounters with the planets cause periodic depletions of particle density. Another model was proposed by Porubčan & Štohl (1992), who thought the outbursts were due to an isolated cloud of small particles from a secondary body of lesser orbital period that separated from the parent comet 1861 I (P/Thatcher). Both models are unlikely. The expected spread in orbital period of the meteoroids will quickly smear out any density variations and the presence of a meteoroid stream in a short period retrograde high inclination orbit is unlikely (Kresák 1958). Kresák proposed that a filament of dust may be brought accidentally in collision with the Earth as a result of planetary perturbations. Trails of dust have been discovered in the orbit of short period comets and have a width consistent with the duration of meteor outbursts (Sykes et al. 1986, Sykes & Walker 1992).

This paper presents observations of a third outburst of Aurigids that does not fit in a simple periodic pattern. The event is described in some detail in Sect. 2 and serves to illustrate far-comet type meteor outbursts. In Sect. 3, the result is added to outbursts of this and other such streams in order to examine the possible role of planetary perturbations. A correlation with the reflex motion of the Sun is found and discussed in the context of the trail hypothesis. The result has implications for interpreting historic accounts of meteor outbursts and allows a forecasting of future events, examples of which are given in Sect. 4.

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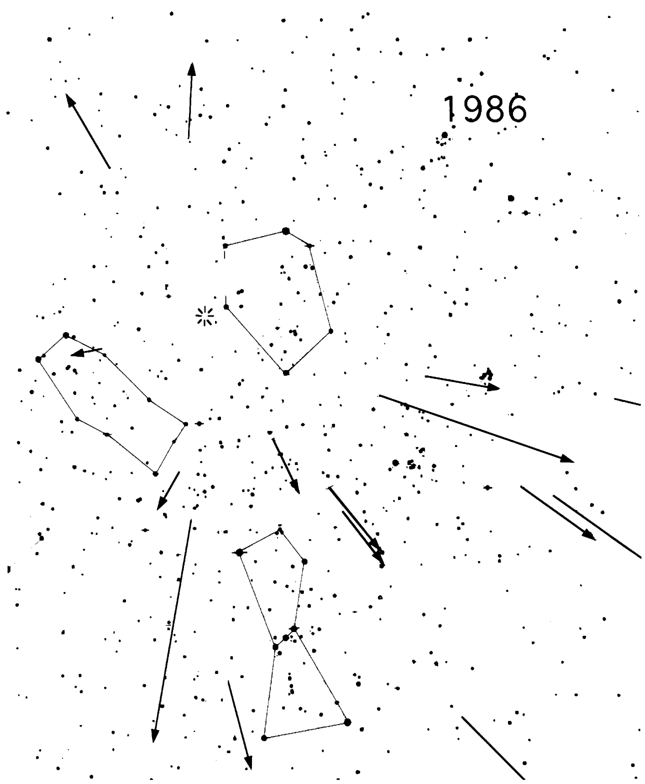

Fig. 1. Observing chart of possible Aurigid meteors from the outburst of 1986 by I. Tepliczky, Hungary. The theoretical radiant of comet P/Kiess is in the constellation Auriga.

2. A new far-comet type meteor outburst

2.1. Aurigids and θ Aurigids

The Aurigid meteor stream is known from two brief outbursts of meteors in the night of September 1 of 1935 and 1986 (Guth 1936, Hoffmeister 1936, Tepliczky 1987). Guth (1936) associated the event with long period comet 1911 II (P/Kiess). The theoretical radiant of P/Kiess is at RA,DEC = (90.5,+39.3 - V_∞ = 67 km/s) at equinox 1950.0, near the star θ Auriga. Guth found 5 plotted meteors to radiate from (87.1,+40.5) with a radiant diameter of 2 degrees, while Teichgraber placed the radiant at (85.1,+40.5) (Hoffmeister 1936). In 1986, observer I. Tepliczky placed the radiant at (94.3,+36.3). His records are shown in Fig. 1. Both outbursts occurred when the Earth was near the orbital plane of the comet, which has a node at solar longitude $\lambda_\odot$ = 157.964 degree (Eq. 1950.0) (Marsden 1983).

The association with P/Kiess is put in doubt by radiant positions quoted for the annual Aurigid meteor stream. This radiant should be close to the P/Kiess position with a relatively small dispersion, given the near head-on encounter conditions and high inclination retrograde orbit (e.g. Kresák & Porubčan 1970), but the BAA Handbook places the radiant far from the P/Kiess position at RA,DEC = (74,+43) on August 28, $\lambda_\odot$ = 156. This result dates back to at least the work of W.F. Denning. Cook (1973) reports a radiant at (84.6, +42.0), the origin of which is unclear.

Reason for the confusion may be that fast Aurigid-like meteors scatter from a wide area in Auriga and Perseus in late August and the beginning of September (e.g. Jenniskens 1990). In late August, fast meteors radiate from (56,+40 - 69 km/s) at solar longitude $\lambda_\odot$ = 148-152 (two meteors in McCrosky & Posen 1961) and from (92,+58 - 57 km/s) at $\lambda_\odot$ = 157-160 (stream IX in Babadzhanov & Kramer 1965). Also, Porubčan & Gavajdová (1994) list a stream of bright meteors at (47,+39 - 65 km/s) in early September, at $\lambda_\odot$ = 165-170. A single meteor photographed during the peak of the annual shower on August 31, 1952, has a radiant at (82,+42 - 69 km/s) (McCrosky & Posen 1961) and some confirmation of an associated minor stream comes from a possible early stream member photographed by the Dutch Meteor Society in 1988, with a radiant at 60.9±0.7,+42.4±0.4 at a time 17 degrees earlier in solar longitude (Betlem et al. 1989).

This implies that the reported annual activity of "Aurigids" in Jenniskens (1994) and Rendtel (1990), based on a diffuse radiant near the above positions, does not reflect the annual activity of the θ-Aurigids of P/Kiess.

Because the annual activity is the baseline for defining anomalous meteor activity, the annual θ-Aurigid stream was revisited. R.D. Lunsford, G.J. Zay, K. Miskotte, M. Langbroek and the author collectively amassed 24.3 hours of effective observing time in 1992, 1994, and 1995 in the period August 28 until September 03 and provided plottings on gnomonic maps from which 26 meteors were classified as annual θ-Aurigids. The activity profile is ill defined and has a peak *Zenith Hourly Rate* (Jenniskens 1994) of ZHR_{max} = 3±1 at solar longitude $\lambda_\odot$ = 158.0±0.5 (Eq. 1950) and a slope B = 0.5±0.2, given that such activity profiles are usually well described by a profile of the general shape (Jenniskens 1994, 1995):

$$ZHR = ZHR_{max} 10^{-B|\lambda_\odot - \lambda_\odot^{max}|} \quad (1)$$

Hence, the annual activity is a factor of three less than given in Jenniskens (1994) and the activity profile may be narrower by a factor of two. However, even with these scaled down values, the total mass in the stream adds up to about 10^{15} g if the orbital period is that of comet P/Kiess, which is of order P $\sim 2 \times 10^3$ years (Lindsey 1932, Marsden 1983).

2.2. A new θ-Aurigid outburst

In the night of September 1, 1994, a third θ-Aurigid outburst was recorded by visual observers Robert D. Lunsford and George J. Zay from Descanso, California (116.6W, +32.8N) (Zay & Lunsford 1994) and is now confirmed by radio meteor scatter observations. Raw data were made available for analysis and will be compared to those of the 1986 outburst, which was seen visually from Hungary and of which raw data were made available by observer Istva'n Tepliczky.

2.2.1. Visual observations

Lunsford and Zay observed under a clear and transparent sky and noticed fast and bright meteors shortly after the P/Kiess radiant

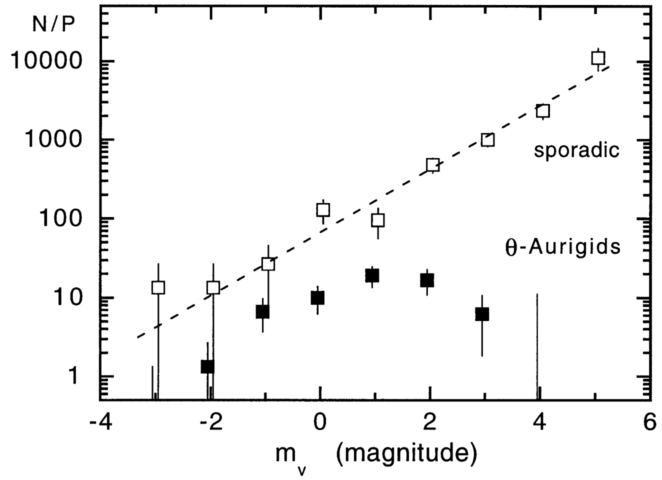

Fig. 2. The magnitude distribution of Aurigids (■) and sporadic meteors (□) in a combination of counts from 1986 and 1994, after correction of the count N(m) for detection probability P(m), i.e. N/P, with P(m) from Jenniskens (1994). The sporadic data are displaced upward by one decade for clarity.

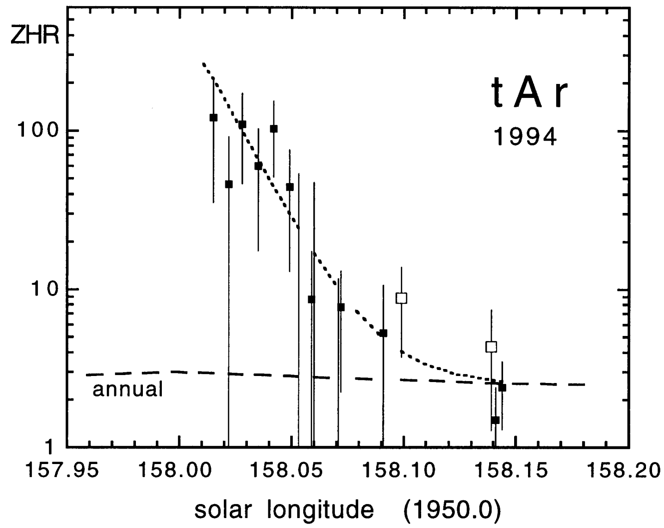

Fig. 3. Visual Aurigid frequency in terms of Zenith Hourly Rates in the night of Sept. 1, 1994. Dashed lines are the annual background and a fit to the total outburst activity. Data by G. J. Zay, R.D. Lunsford, from Descanso, CA (■), and the author from San Jose, CA (□).

rose above their local horizon at 06:55 UT. Observations had started hours before and the sudden appearance of long streaks from the Eastern horizon was very conspicuous. Their estimated angular velocity was about 30 degrees per second. The meteors were described as white tinged with blue or green and leaving a smoky trail of at least 45 degree long. The two brightest Aurigids were intensely orange colored.

From 07:20 UT onwards, in periods of 10 minutes, a total of 2,1,3,2,4,1,0,0,1 Aurigids were observed by Zay and 1,1,2,2,2,2,0,1,0 Aurigids were seen by Lunsford. Because both observers were watching from the same location and many meteors were bright and were seen by both observers, these are not two independent datasets. If both observers are considered one, the count is similar to Zay's and is (starting at 07:20 UT): 2,1,3,2,4,2,0,1,1 per 10 minutes, and none before that time. The magnitude distribution of these individual Aurigids was (from +5 down, starting at the interval +5.5 to +4.5 and in steps of one magnitude): 0,0,2,3,9,1,0,1.

The dominant presence of magnitude +1 meteors is consistent with magnitude estimates by Tepliczky during the 1986 outburst. With the radiant high in the zenith, he counted (from +5 down): 0,0,0,5,3,6,5 Aurigids. The combined magnitude distribution is shown in Fig. 2 and suggests that the particles in the stream are not distributed according to a power law, but are predominantly of masses 10^{-4} to 1 gram (diameter $\sim$ 0.06-1.2 cm). A slope χ = n(m+1)/n(m) = 1.3±0.3 is found from the ratio of sporadic and stream members at magnitudes fainter than -1.

In the calculation of Zenith Hourly Rates from the raw meteor counts, one should account for the lack of faint meteors when choosing the exponent of the radiant altitude (h_r) correction γ, where rates scale with $sin(h_r)^{-\gamma}$ (Jenniskens 1994). I have adopted γ = 1.08. The star limiting magnitude (Lm) was close to standard and has little influence. The resulting activity curve is shown in Fig. 3. Only the descending branch is observed. The activity profile has a slope B = 26±8 and a peak ZHR of 400, give or take a factor of two (depending on B), if the peak position is at $\lambda_\odot$ = 158.003 (Eq. 1950) - see below.

Table 1. Results from exponential curves fitted to the ZHR data of annual and outburst θ-Aurigids. "Nr." refers to the catalog of outbursts in Jenniskens (1995). $\lambda_\odot^{max}$, ZHR_{max} and B refer to parameters in Eq. 1. The magnitude distribution index χ = n(m+1)/n(m) is the ratio of the number of meteors in two adjacent bins after correction for observability (Jenniskens 1994) and is valid for the magnitude range m_v = -1 to +4.

Nr.	Name	Year	$\lambda_\odot^{max}$	ZHR_{max}	B	χ
	annual:					
	tAr		158.0±0.5	3.0±1.0	0.5±0.2	$\sim$3
	outbursts:					
34	tAr	1935	$\geq$157.950	$\geq$100	35±15	2.2
35	tAr	1986	157.821±0.002	250±30	33±8	1.3
69	tAr	1994	158.003±0.005	$\sim$400	32±4	1.7?

2.2.2. Radio Meteor Scatter observations

At the time of the event, radio amateurs (hams) found it easy to establish meteor-scatter contacts at 144 MHz. One observer F1FIH (4.5E,+43.8N) reported that all bursts were longer than 10 seconds (i.e. meteors brighter than about magnitude m_r = +1, McKinley 1961) and contacts were made from 08:03 UT, when the operator noticed something was happening, until 08:15 UT (Gottsche 1995).

The event left a 35 sigma peak on the recordings of the automatic meteor counting system of Ilkka Yrjölä from Kuusankoski, Finland (26.4E, +60.9N), which is based on radio forward meteor scatter. The system consists of a two-element Yagi antenna with gain 4 dB aimed at the horizon at azimuth

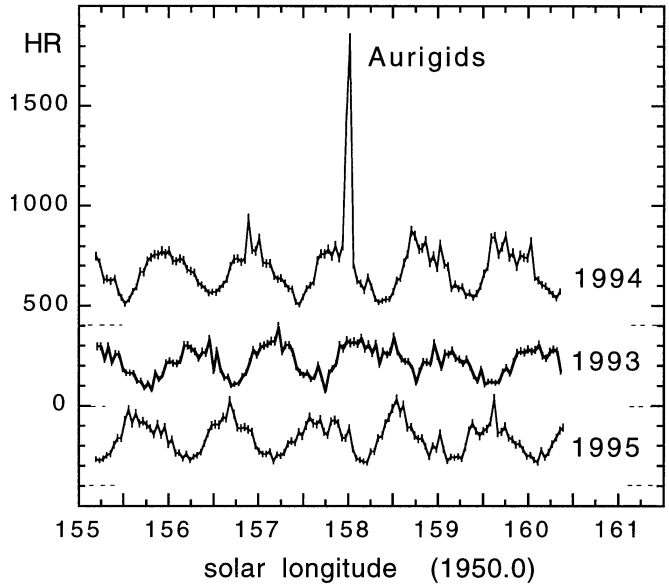

Fig. 4. Hourly rate of threshold crossings of reflected radio emission intensity for the period August 29-Sept. 03 in three consecutive years (data: I. Yjölä).

45^o (SW), and a narrow band FM receiver that listens to the transmitted power at 87.360 MHz, mainly from a radio station in Hamburg, Germany. Meteor reflections that raise the output signal above -122 dBm are fed in binary form in a T-1000 SE computer. Note that each overdense echo may contribute to several threshold crossings.

Figure 4 shows the hourly rate of radio reflections in the period August 29 to Sept. 03 in three consecutive years. Only in 1994 a sharp increase in reflections was observed on September 1. This peak coincides with the visual report of the Aurigid outburst. The total count of threshold crossings increased significantly in two consecutive hours, centered at solar longitudes 157.978 (6:30 UT) and 158.018 (7:30 UT), which had 704 and 1106 detections respectively above a background of 290 counts per hour with a root-mean-square variation of 37 counts per hour, close to saturating the system. Note that many overdense echoes may have been counted several times. The peak of the shower was at solar longitude 158.003+/-0.005 assuming a profile given by Eq. 1. The longest reflections recorded during the outburst lasted 22 and 17 seconds in each interval (m_r about -1).

Table 1 compares the observations to those of previous Aurigid outbursts. The outburst of 1994 is found to be similar to previous descriptions with respect to the activity curve, the time of maximum, and the mean brightness of the meteors.

3. Discussion

3.1. Correlation with planet positions

The 1994 Aurigid outburst came at a time when the positions of the planets Jupiter and Saturn were much the same as in 1935. In both 1994 and 1935 Saturn was in conjunction with the stream, at solar longitude 158 and 157 degree respectively (the solar longitude being the longitude of the Sun as seen from the planet), while Jupiter was at solar longitude 48 and 57 degree. In 1986, the situation was reversed: Jupiter was at solar longitude 167 and Saturn at 69 degree.

The alpha-Monocerotid stream shows a similar repetitive pattern of planet positions during outbursts. In 1925 and 1985, Saturn was at solar longitude 49 and 61 degree respectively (with the ascending node of the stream at 59 degree) and Jupiter was at 119 and 141 degree, while in 1935 Jupiter was at 64 and Saturn at 160 degree.

This repetitive pattern consists of two unequal intervals of 10 and 50 years and we have not missed a single Aurigid or alpha-Monocerotid outburst since their first sightings if these are the only favourable planet positions.

In the case of the Lyrids, there is only one configuration, when both planets are almost in conjunction with the node of the stream. The four strongest outbursts of Lyrids occurred when Jupiter and Saturn were at solar longitude 20$\pm$15 and 10$\pm$16 respectively, the descending node of the stream being at solar longitude $\lambda_\odot$ = 31.0. This effect was first noticed by Guth (1947).

Conjunctions with the node of the stream are also common among other possible far-comet type outbursts of which only a single apparition has been reported (Jenniskens 1995). Six out of ten had Jupiter within 20 degrees from the nodal line of the mean meteoroid orbit.

3.2. The Sun's reflex motion

However, note that conjunctions are rather frequent, at least once every 12 years in the case of Jupiter alone. Outbursts, on the otherhand, are reported only if both Jupiter and Saturn are at favorable positions.

I now find that the two diffrent planetary configurations associated with Aurigid and alpha-Monocerotid outbursts have almost equivalent displacements of the Sun from the barycenter, defined as:

$$\Delta R = -\Sigma_i \frac{m_i}{(M_\odot + m_i)} R_i \qquad (2)$$

where the summation is over the 9 planets (where Jupiter and Saturn account for most of the total), m_i is the mass of the planet i, $M_\odot$ the mass of the Sun, and R_i the heliocentric distance of planet i.

The significance of that result is illustrated in Figure 5, which shows the location of the Sun with respect to the barycenter on the date of September 1 for all years in the period from 1900 until 1995. The X-axis is chosen in a direction from barycenter to Earth, hence the Earth is to the right of the diagram at 1 AU. The revolution of the planets causes a cyclic reflex motion of the Sun around the barycenter that, over time, samples a region up to a maximum of $\pm$0.010 AU if all planets are aligned. As much as $\pm$0.005 AU of that displacement is due to Jupiter's influence alone, another $\pm$0.003 AU from Saturn. Uranus and Neptune account for much of the remaining $\pm$0.002 AU. Each year that an outburst might have been reported is given by an open circle.

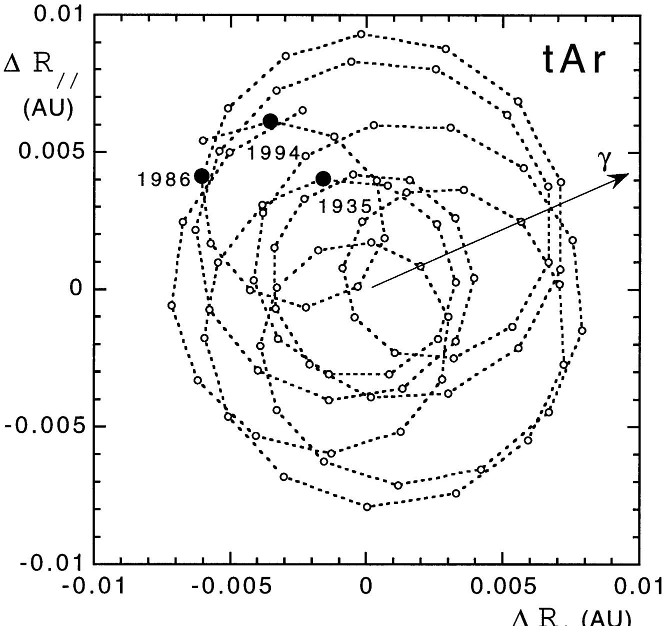

Fig. 5. Displacement of the Sun from the solar barycenter (in Astronomical Units) in the plane of the ecliptic on the date of September 1 in the period 1900-1995. The position in each year is marked by an open circle, while the years when Aurigid outbursts were observed are marked by solid circles. The Earth is located at 1 AU to the right of the diagram and moves counter clockwise.

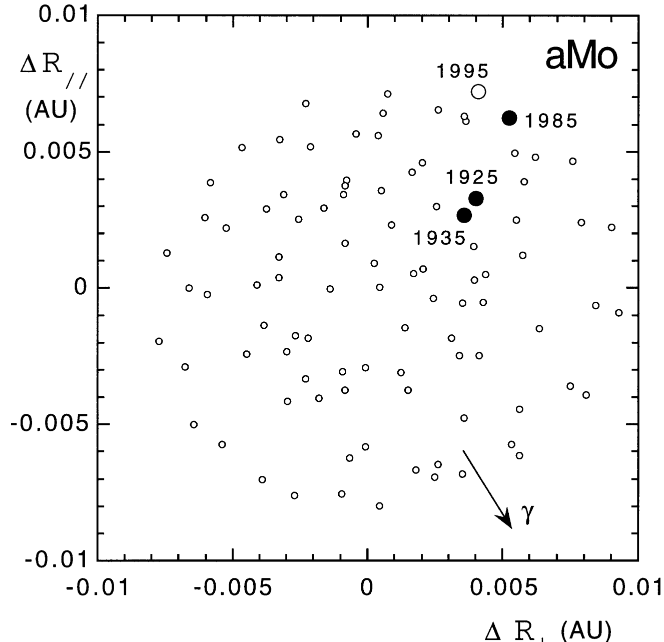

Fig. 6. Same as Fig. 5 for the alpha-Monocerotid shower. The dashed line is omitted. The situation in 1995 is highlighted.

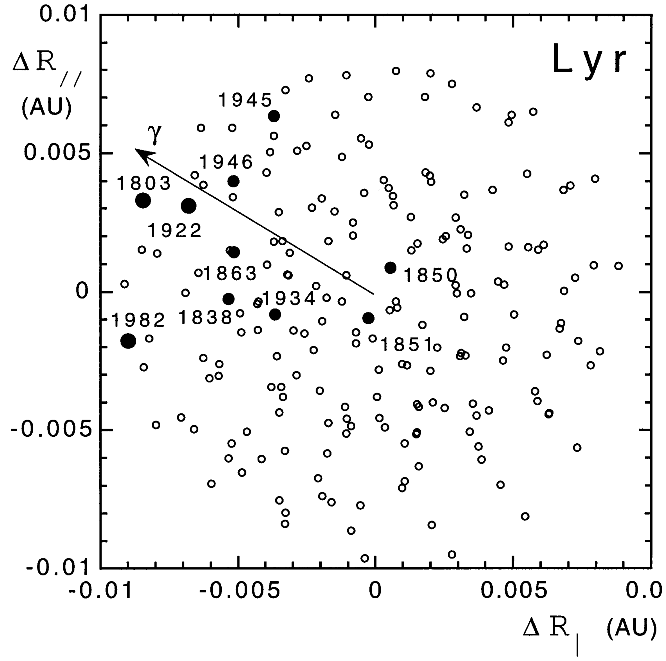

Fig. 7. Same as Fig. 5 for the Lyrid shower in the period 1800-1995.

The three years that such outbursts did occur are given as solid circles. The width of the stream is roughly equal to the size of these solid circles. Note that the sightings cluster in a small part of the diagram, but do not exactly coincide.

Figure 6 shows the same diagram for the alpha-Monocerotid stream. Again, all three returns cluster in a small part of the diagram. Figure 7 shows the same diagram for the Lyrid stream, now with all sampled positions in the years between 1800 and 1995, because the first well documented Lyrid outburst was already seen in 1803. Of course, many outbursts may have been missed since, but the years that such were reported cluster again in a small part of the diagram, with the best documented outbursts (perhaps the most intense) when the displacement was most extreme (large symbols in Fig. 7). The likelihood of three such groupings in 1/10th of the available parameter space out of a sample of three streams is about 1 in 10^6.

3.3. Sample bias?

The odds are less impressive if there is a bias in the data with a period of about 12 years, similar to the orbital period of Jupiter (which accounts for the main periodicity in the reflex motion of the Sun). For example, the solar activity cycle has approximately that period, but can be excluded on the ground that meteor outbursts do not strongly correlate with transient solar phenomena and the effect of solar activity on annual streams is modest, affecting rates at best 50% (Lindblad 1978, Jenniskens 1994).

A 12 year periodicity in the visibility of a meteor stream might occur due to a preferred location of the observers on one quarter of the globe in combination with phases of the Moon (Guth 1947). However, such sampling bias can also be excluded on the ground that meteor outbursts are reported by observers from all parts of the globe, even during periods of moonlight (e.g. Jenniskens 1995). Accounts of the Aurigid outbursts were

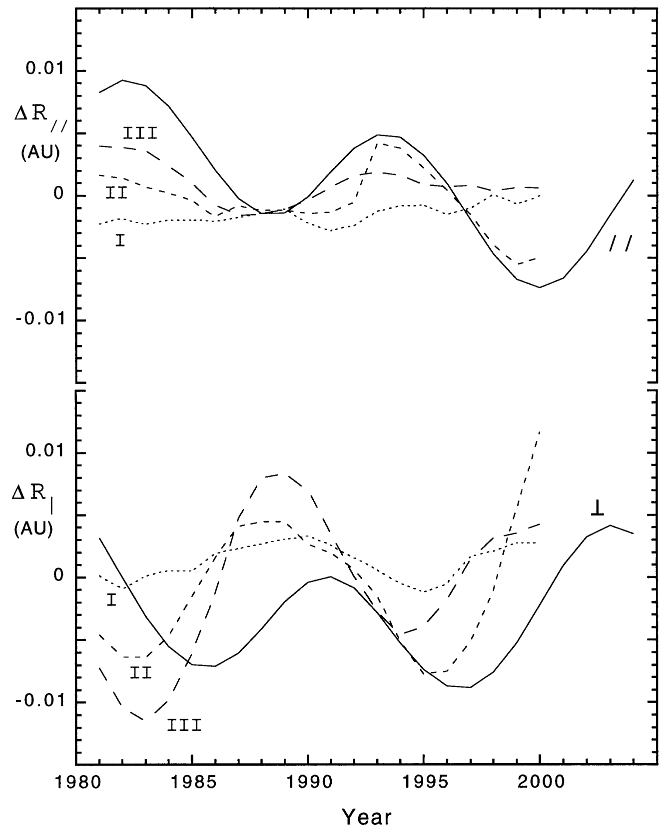

Fig. 8. Displacement of the center of the Perseid stream in the plane of the ecliptic near the descending node in three stream models of Wu & Williams (1993). The upper graphs show the displacement parallel to the Earth's orbit, which reflects the time of maximum of the shower. The lower graphs show the displacement perpendicular to the Earth's orbit, which reflects the years of a close encounter. The solid line is the displacement of the Sun from the barycenter as in previous figures.

reported from Europe (twice) and the western USA, accounts of the α-Monocerotids are from India, the western USA and Europe, while Lyrid outbursts were seen in the eastern USA (two times) and in Europe.

3.4. Displacements of a trail of dust

The Sun's reflex motion may be a (distorted) image of the relative displacement of a trail of dust with respect to the Earth's orbit as a result of planetary perturbations. Only when (not so accidentally as we have seen now) the trail intersects the Earth's orbit is a meteor outburst observed (Kresák 1958). Such trails of dust have been discovered in the wake of some short period comets and have a width consistent with the duration of meteor outbursts (Sykes et al. 1986, Sykes & Walker 1992).

The type of motion inferred from the observations is present in recent models of the Perseid meteor stream by Wu & Williams (1993). The Perseid meteoroids were followed for one orbital revolution after ejection and the intersection point of the meteoroid orbits with the ecliptic were plotted as a function of time. The Perseid stream has a relatively long period, P = 135 years, and these models should be representative of other streams with long period high inclination retrograde orbits.

The modelling resulted is an oscillation of the center of the stream with an amplitude of about 0.005 AU. The displacement of the center of the stream in the three published models, parallel and perpendicular to the Earth's orbit, are compared to the displacement of the Sun with respect to the barycenter in Fig. 8. Although there is no perfect correlation, the displacement at a given time does reflect the barycentric displacement of the Sun at that time in amplitude, with a possible phase lag for the perpendicular motion. The signs are such that, while the Earth follows a path around the barycenter, the cometary grains seem to change course following the Sun's center of gravity.

It is not clear how well the model represents nature, but the observations seem to agree with the model in that the variations have an amplitude similar to the solar reflex motion. The maximum amplitude of the solar reflex motion, 0.01 AU, is larger than the minimum distance between Earth's orbit and the orbit of the two known parent comets that are responsible for far-comet type meteor outbursts, P/Thatcher (Δ = 0.003 AU) and P/Kiess (0.006 AU). Some intrinsic deviation from a strict correspondence between the Sun's reflex motion and a possible trail displacement (including phase lags) are present in the data (Fig. 5-7), just as in the model.

If the years of good displays correlate with the barycentric motion of the Sun because of a displacement of a trail like structure perpendicular to the Earth's orbit, then one might also expect a correlation with the time of peak activity, which reflects the displacement of the trail parallel to the Earth's orbit. There is some indication that this is the case. The Aurigids of 1935 and 1994, when Saturn lined up with the node of the parent comet, were both later than the event in 1986, when Jupiter was at the nodal line. But again there is significant scatter from any tight correlation with the barycentric position of the Sun. Figure 9 shows the situation for the Lyrid stream. On the X-axis is given the time of peak activity for Lyrid outbursts in the past, while the Y-axis gives the barycentric displacement of the Sun parallel to the Earth's orbit. The dotted lines have a slope as expected if there is a one-to-one correlation between the displacement of the Sun and the displacement of the trail with respect to the Earth. I leave it to the reader to judge if this is evidence for the existence of two Lyrid trails, perhaps from before and after a recent perturbation of the parent P/Thatcher. Note that the outburst in 1982 was slightly broader than that in 1922 (Jenniskens 1995), suggesting that older material may have been sampled. Future observations of this shower may shed light on the significance of this result.

The trend that meteor outbursts correlate with conjunctions of one of the planets with the node of the stream suggests that the best opportunities for observing a meteor outburst are when the displacement is largest. That may account for the rich crop of such outbursts in the period 1981-1986, when all major planets were aligned. It is possible that the number density of cometary orbits decreases closer to the Earth's orbit. The Earth may be more effective in disturbing the parent comet, or in depleting the meteoroid stream, when the trail is more frequently intersected.

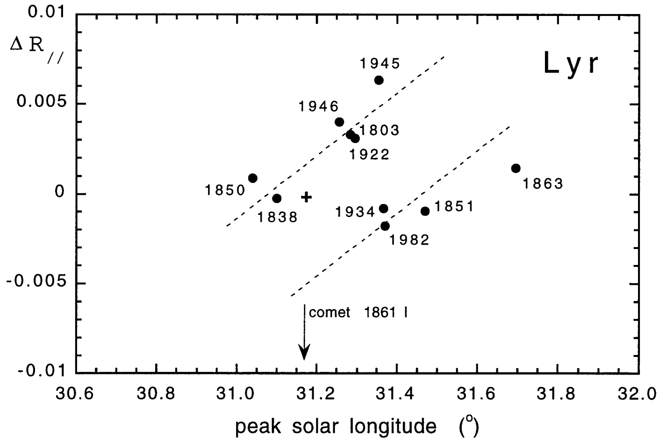

Fig. 9. The barycentric displacement of the Sun parallel to the Earth's orbit at the time of outbursts is plotted versus the position of the stream along the Earth's orbit as derived from the time of peak activity. The dashed line has a slope equal to 57.3 degree per Astronomical Unit (360 degrees being 2 π AU).

Table 2. Historic outbursts that have been associated with the Lyrid stream. Solar longitudes ($\lambda_\odot$) are in Equinox 1950.0. The barycentric displacement of the Sun (Δ) is in units of 0.001 AU. Note that before 1800 only Jupiter's and Saturn's influence is included (*). Data by [1] Jenniskens 1995; [2] Guth 1947; [3] Biot 1846; Newton 1963, 1964; [4] Denning 1884; [5] Olivier 1925; and [6] Tian-shan 1977.

Year	Date	$\lambda_\odot$ Earth	$\lambda_\odot$ Jupiter	$\lambda_\odot$ Saturn	$\Delta_\vert$	$\Delta_{//}$	Ref.
1982	Apr 22.3	31.371	035	020	-9	-2	[1]
1945	Apr 21.8	31.355	356	283	-4	+6	[2]
1946	Apr 21.9	31.253	024	296	-5	+4	[2]
1934	Apr 22.0	31.366	020	142	-4	-1	[2]
1922	Apr 21.8	31.296	016	007	-7	+3	[1]
1863	Apr 21.1	31.695	024	005	-5	+1	[3]
1851	Apr 20.8	31.47	020	208	+1	+1	[2]
1850	Apr 20.1	31.04	354	194	-0	-1	[4]
1838	Apr 20.1	31.10	349	057	-5	-0	[5]
1803	Apr 20.3	31.283	005	352	-8	+3	[3]
840	Apr 01.0	30.9	331	104	-3*	+2*	[5]
582	Apr 01.0	(32.0)	025	175	-3*	-1*	[2]
464	Apr 01.5	(33.7)	043	174	-3*	-3*	[6]
-14	Mar 27.7	31.5	303	095	-1*	+3*	[3]
-686	Mar 23.7	31.8	060	159	-3*	-5*	[3]

3.5. The cause of the displacements

The cause of the oscillations in the osculating orbital elements of the meteoroids near the Earth's orbit is not merely one of a changing gravitational potential well. This would both affect the Earth and the meteoroids. Close approaches to the planets do not play a role either. Note that the Bootids (Quadrantids), which have an aphelion close to the orbit of Jupiter, do not have their activity vary strongly with the Jovian period. The strong activity in one year and absence in another excludes the hypothesis that planets cause periodic depletions of particle density (Guth 1947). The cause is also not in variations of the solar wind pressure, a feature that was not part of the numerical models of Wu & Williams (1993).

Rather, the cause of these oscillations may be the reflex motion of the Sun itself. At large perihelion distances the Sun's velocity becomes non-negligible with respect to the velocity of the particles. Alternatively, Jupiter accelerates and decelerates particles in a given orbit during its revolution around the Sun, depending on the relative direction of the velocity vectors. Further study of this multi-particle problem is warranted, because it is not intuitive why the resulting oscillations have an amplitude and phase as found in the models.

4. Implications

These results allow new interpretations of historic accounts of outbursts and the forcasting of future events.

4.1. Historic Lyrid outbursts

There are many historic accounts associated with the Lyrid stream, dating back to 687 BC. The mere presence of the outbursts implies that the orbit has changed only marginally over time during the past six or so orbital revolutions of the parent comet, which may be on account of the orbit's high inclination ($i = 79.8^o$). However, small changes are expected. A change in the barycentric position of the Sun during outbursts can give information about such subtle orbital changes.

The positions of Jupiter and Saturn at the time of historic Lyrid outbursts were derived from the geocentric longitude tables of Stahlman & Gingerich (1963) and are listed in Table 2. The table also gives the barycentric displacement of the Sun due to these two planets alone, which is ± 0.002 AU of the total.

It is found that historic outbursts, too, correlate with planet positions. Three of the historic outbursts (in 582 AD, 464 AD and 686 BC) occurred when Jupiter was in conjunction with the node of the stream. Saturn was in all cases close to $\lambda_\odot$ = 180 degree, opposite the position during the recent outbursts of 1803, 1922, and 1982. Two other events in 840 AD and 15 BC occurred when Jupiter was not in conjunction with either node of the stream. In both cases, however, Jupiter and Saturn were at a similar location and the times of peak activity were about 0.6 degree earlier in solar longitude than for the other events. The resulting barycentric displacement perpendicular to the Earth's orbit is similar for both cases and somewhat less than for modern outbursts. Hence, it seems that in historic times the gravitational perturbations needed to be slightly different for the dust to collide with the Earth. The data suggest an outward movement of the descending node of the orbit by +0.005 ($\pm$0.002) AU in a period of two millennia. The motion parallel to the Earth's orbit in that time period was some +0.003 AU/1000 years, which compares to the predicted mean nodal motion of +0.010 AU over the past 1000 years from model calculations by Fox (1986).

Table 3. Possible far-comet type outbursts from the catalog of Jenniskens (1995), the year that they were seen last, the date and time of the peak activity, and the next occasions when the Sun has a similar barycentric displacement in the period 1995-2050. Notes: *) Telescopic showers. Outbursts not listed before:

aLy *alpha-Lyncids*, seen by Malcolm Currie, BAA-Meteor Section, at Worlingham, Beccles, Suffolk, U.K on December 20, 1971. Number in four minute intervals starting at 21:55 UT: 7,4,3,1,2,2,1,0 (Lm=+6.6, 9 sporadics). Many meteors seen prior to first count. Radiant at (138,+44). Average magnitude +3.47. $\lambda_{\odot}^{max} \leq 268.055$, B = 60±20, $ZHR_{max} > 200$. Background rate ZHR ∼ 8.

Pyx *alpha-Pyxisids*, observed by Tim Cooper, ASSA-Meteor Section, at Sasolburg, South Africa on March 6, 1979. Number of Pyxids in 10 minute intervals starting at 19:00 UT: 4,0,1, 2,0,2, 0,1,1, 0,1,1 (Lm = +5.5, 3 sporadics). Radiant at (135,-35). Magnitudes from +5 down: 0,3,5,1,4. $\lambda_{\odot}^{max} \leq 345.213$, B ∼ 30, $ZHR_{max} \geq 40$. Background rate ZHR ∼ 10.

aCi *alpha-Circiniids*. Belinda Bridge, Queensland, Australia, reported seeing large numbers of meteors on June 4, 1977, around 10:30 UT, with rates falling off around 11:00, and activity over by 11:20 (Meteor News 40, 1977). Radiant near (218,-70). $\lambda_{\odot}^{max} \leq 73.31$. B ∼ 35, $ZHR_{max} \geq 60$.

	Stream	Date	$\lambda_{\odot}^{max}$ (1950.0)	Next returns in:
Lyr	Lyrids	1982 Apr 22	031.4	2016/17?, 41/42
aBo	α-Bootids*	1984 Apr 28	037.5	2018?
aCi	α-Circiniids	1977 Jun 03	072.4	2003, 27/28, 49
gDe	γ-Delphinids	1930 Jun 11	079.7	2002/3, 13, 27/28
kPa	κ-Pavonids	1986 Jul 17	114.1	1995/6, 2019/20
bPe	β-Perseids*	1935 Aug 07	134.7	2007, 17/18, 43
bHy	β-Hydrusids	1985 Aug 16	143.1	1995, 2008?, 18/9
tAr	θ-Aurigids	1994 Sep 01	158.0	18/19, 43/44
eEr	ϵ-Eridanids	1981 Sep 10	167.4	2041?
aMo	α-Monocerotids	1985 Nov 22	238.6	1995, 2008?, 18/19
oOr	o-Orionids	1964 Nov 26	243.4	2011, 32/33, 47
aLy	α-Lyncids	1971 Dec 20	268.1	2006/7, 17, 42/43
aCe	α-Centaurids	1980 Feb 07	318.5	2040/1
Pyx	α-Pyxisids	1979 Mar 06	345.3	2004?, 39/40

A series of spectacular westward showers was seen in Europe in the Middle Ages in mid April between 1000 and 1204 AD, close to the date of Lyrid outbursts (Guth 1947, Dall'olmo 1978). The descriptions of these outbursts are inconsistent with other known far-comet type outbursts. Hence, these are not related to P/Thatcher. In stead, they were probably of near-comet type, due to a short period comet with a period of about P = 14 years, or a fraction thereof. A gradual shift in node prior to 1204 suggests that the parent comet orbit was perturbed at that time, moving away from the Earth's orbit.

4.2. *Predicting future far-comet type outbursts*

The previous findings allow the prediction of future outbursts by calculating the planetary perturbations on a stream of dust particles and by matching the resulting oscillating path of intersection points with the ecliptic near the Earth's orbit to that of observed meteor outbursts. Such calculations are beyond the scope of this paper. However, some prediction can be made by simply calculating the position of the planets (e.g. from Montenbruck & Pfleger 1994) and from that the barycentric displacement of the Sun, and by matching the Sun's displacement to that at times of other observed outbursts. Figure 10 shows the future barycentric path of the Sun between 1995 and 2050. The figure varies slightly for different times of the year. Table 3 summarizes the years when the Sun will be close to the same position as during the most recently reported previous meteor outburst.

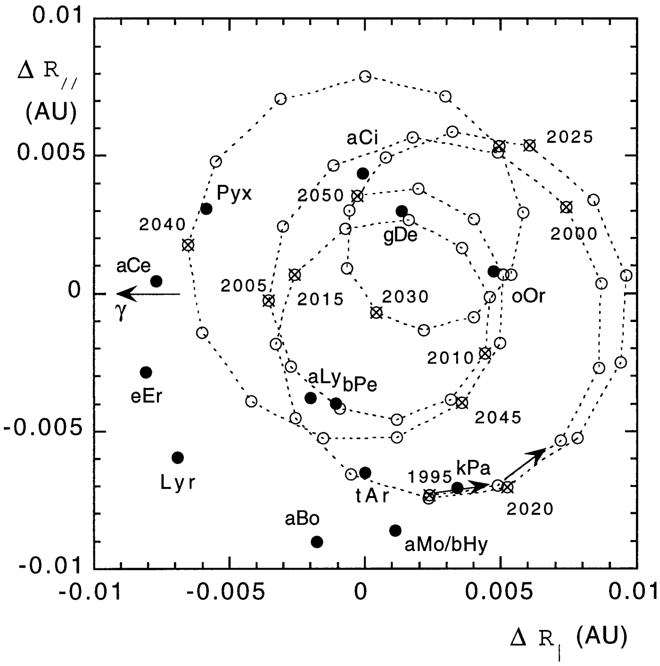

Fig. 10. Diagram as Fig. 5, now showing the barycentric path of the Sun in the near future, between 1995 and 2050. Black dots show the position of the Sun when the meteor streams produced their last far-comet type outburst. Close encounters are listed in Table 3.

The alpha-Monocerotid event in 1995 is anticipated with most confidence (Jenniskens 1995a)*. No outburst was reported in 1994. Other streams are less certain, notably when the identification "far-comet type" is in doubt. For example, no kappa-Pavonid outburst was observed in 1995 during a dedicated observation from Pretoria, South-Africa, covering solar longitude 113.96-114.26 and 114.36-114.38. The annual activity was found to be less than $< ZHR >$ = 0.5. However, it is possible that the stream will return in 1996.

The best opportunity for detecting outbursts of far-comet type of yet unknown meteor streams is expected to be during superior and inferior opposition of Jupiter and Saturn, when the trail displacements are largest at a given time in the year, and especially in the years when Jupiter and Saturn are in conjunction. The next five years are promising and the newly discovered streams may be reobserved 24 years later.

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***)** At the time of revising this manuscript, the alpha-Monocerotid shower had returned as predicted (e.g. reports in Marsden 1995).

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