Astron. Astrophys. 348, 295–299 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Meteor storm forecasting: Leonids 1999–2001

I. Ferrin

Center for Theoretical Astrophysics, University of the Andes, Merida 5101, Venezuela (ferrin@ciens.ula.ve)

Received 15 March 1999 / Accepted 19 May 1999

Abstract. We present a method for meteor storm forecasting, that we apply to the Leonids in 1999–2001. The method makes use of a plot where the particle density distribution around the comet is mapped (Fig. 1) and isolines of equal meteor intensity are drawn. The most significant result found is the existence of a “ridge” or region of high particle density, that corresponds to the great Leonid storms and that we identify with the “dust trails” that Sykes et al. (1990) and Sykes & Walker (1992) found behind all periodic comets. We present detailed calculations of the trajectories of meteoroids that will reproduce this ridge. We predict the intensity of upcoming Leonid showers by the position of the Earth in relation to the isolines. For 1999 we predict a zenith hourly rate (ZHR) of 3.5 K±1 K. For the year 2000 we can only limit the intensity to $5\,K < ZHR < 20\,K$. And for 2001 the ZHR will only reach to 400±100.

Key words: meteors, meteoroids

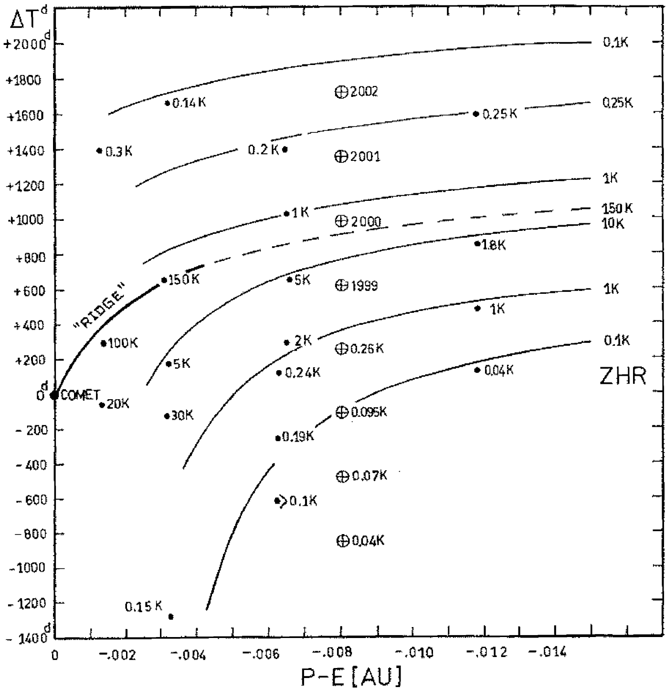

Fig. 1. Particle distribution around comet Tempel-Tuttle. The points have been labeled with the intensity of the shower, ZHR. The isolines have a logarithmic scale. The circle with the cross inside marks the crossing point of the Earth for different years. Notice the existence of a “ridge” or region of enhanced activity over the 150 K point. A profile of the shower along the line joining all the points for the current period (1995–2001) is presented in Fig. 3.

1. Introduction

The Leonid meteor storms are among the most spectacular events that the sky has to offer humanity. Roughly, storms happen every 33 years, although with wide variations in intensity (Yeomans, 1981). With the last spectacular storm in 1966, public and scientific attention has been focused on forecasting the time and intensity of the Leonid showers around the year 1999–2001.

Meteor storm forecasting has many uncertainties relating to the trajectories of particles ejected from the parent comet, in the case of the Leonids, 55P/Tempel-Tuttle. The literature contains several predictions with a wide range of intensities (Yeomans, 1981; Brown & Jones, 1993; Beech et al. 1997; Yeomans et al. 1996; Wu & Williams, 1992, 1995, 1996; Rao, 1998). In this work we present a new method of predicting meteor shower intensities and times, while taking advantage of information from the 1998 shower.

2. The method

Our method is based on Fig. 1 which plots ΔT vs P-E, where P-E is the distance of the particle in the comet orbit to Earth, at closest approach, and ΔT is the time elapsed between the comet and the Earth at the node. This plot has been done before by many authors (Davies & Lovell, 1955; McIntosh, 1973; Yeomans, 1981; Wu & Williams, 1992; Brown & Jones, 1993). What is different in our work is that while previous authors label the points with the year of observations, *our Fig. 1 labels the points with the intensity of the shower*, ZHR. This allows lines of equal intensity (isolines) to be drawn empirically. In this way the particle distribution around the comet is mapped and clearly exhibited.

Several isolines have been drawn in Fig. 1 from data taken from Yeomans (1981), Rao (1998), Mason (1995), and Arlt (1998), listed in Table 1. For those years for which a range of values is given, we have selected that value that best agrees with the surrounding points. Some isolines are missing or incomplete

---

Send offprint requests to: I. Ferrin, Apartado 700, Merida 5101-A, Venezuela (ferrin@ciens.ula.ve)

Table 1. Intensity of the Leonid Meteor Shower vs Time (Units, 1 K)

Year	*Yeomans* (1981)	*Rao* (1998)	*Mason* (1995)	*Arlt* (1998)	*Adopted*
1998	–	–	–	0.26	0.26
1997	–	> 0.1	–	0.095	0.1
1996	–	–	–	0.07	0.07
1995	–	–	–	0.04	0.04
1969	0.14	–	–	–	0.14
1966	150	< 150	–	–	150
1965	5	0.12	–	–	5
1961	0.16	–	–	–	0.16
1932	0.24	–	–	–	0.24
1931	–	–	0.19	–	0.19
1930	–	–	> 0.1	–	> 0.1
1903	0.25	–	–	–	0.25
1901	144*	0.85–1.8	–	–	1.8
1900	> 1	> 1	> 1	–	1
1899	0.04	–	–	–	0.04
1869	–	–	0.2	–	0.2
1868	1	1–1.8	–	–	1
1867	5	2.2–5	–	–	5
1866	2	2–7.2	–	–	2
1836	0.3	–	–	–	0.3
1833	50	50–150	–	–	100
1832	20	20	–	–	20
1799	–	30	–	–	30

* The 1901 point given by Yeomans as ZHR= 144 K, seems to have been a misprint carried over from a previos paper, according to Mason. Rao cites a much lower value.

due to the lack of observational data. In spite of the data scarcity the distribution of particles around the comet is clearly mapped. Fig. 1 corresponds to quadrants I and II of Yeomans' (1981) Fig. 3.

Zenith hourly rate, ZHR, is defined as the number of meteors seen by a single observer under ideal conditions: the radiant at the zenith, and a limiting visual magnitude of 6.5. These requirements are seldom met. Thus there is a problem with ZHR in that it is not a measured quantity, or trivially obtained from the measured flux of meteors. ZHR is derived multiplying the observed flux by two corrections, zenital distance and limiting visual magnitude of the sky (Zvolankova, 1983). These corrections are usually large, and in some cases (low altitude, bright sky) may reach a factor of 10. For example the ZHR of 79 reported for the Leonids in 1994 (November 18th, 06 hrs), was actually based on observing 8 meteors in 30 minutes. In general, the published ZHR is a factor much greater than the number of meteors observed, and differente authors may reach a different multiplier, specially for old data for which the observing conditions are unknown. This explains why some data points in Table 1 and Fig. 1, do not agree with the surrounding points.

The most revealing feature of Fig. 1 is the existence of a "ridge" emanating from the comet at the level of ZHR=150 K! That is, there is a locus of points in the ΔT vs P-E plane that corresponds to the great Leonid storms. The meteoroid density decreases with distance from this ridge. We have identified this ridge with the dust trails studied by Sykes et al. (1990, 1992). According with their results all periodic comets have behind them dust trails of enormous extension, characterized by large particles.

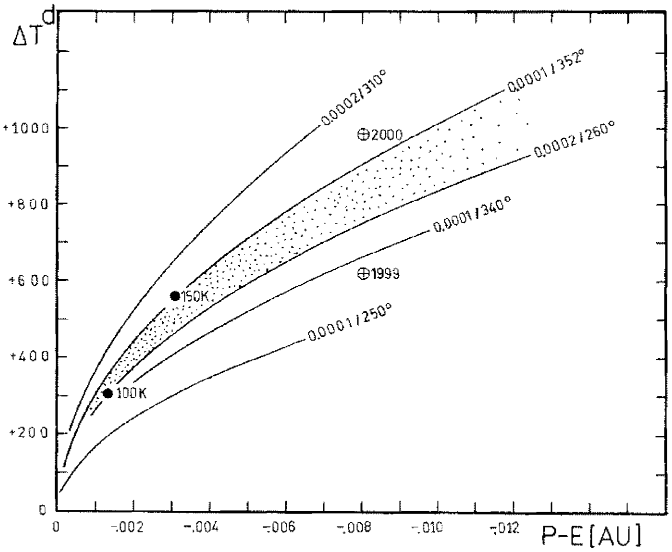

Fig. 2. Diagram of particle distribution for several combinations of β and ν. The 100 K and 150 K points help to constrain the models to values of β between 0.0001 and 0.0002. Notice the appearence of a region of enhanced activity. In reality the edges are not sharp.

Note also that the isolines are labeled in logarithmic scale, and that the 100 K isolines above and below the ridge are missing due to the lack of observational points to substain them. The circles with a cross inside mark the position where the Earth intercepts the orbital plane of the comet, according to Yeomans' data (1981).

Unfortunatelly the isoline that defines the ridge does not extend far enough to predict the intensity for the year 2000. That is why the extension of the ZHR=150 K isoline has been drawn with dashes. Notice that above the ridge the intensity of the shower decays very steeply making any prediction difficult. In particular, the position of the ridge is critical for predictions of the Leonid strength in the year 2000. In the next section we will calculate particle trajectories so as to allow for the extension of the ridge.

3. Calculations

To make a reliable prediction we need to calculate where the particles ejected from the comet are located in space. McIntosh (1973) has calculated the change in orbital elements of particles ejected from the comet. These changes in the semi-major axis, a, and perihelion distance, q, are

$$\frac{da}{a} = \frac{1}{1-e} \tag{1}$$

$$\left[\beta\frac{1+e^2+2ecos\nu}{1+e} + \frac{2ev_\mathrm{r}}{V_\mathrm{q}}sin\nu + \frac{v_\mathrm{b}}{V_\mathrm{q}}(1+ecos\nu)\right]$$

$$\frac{dq}{q} = \beta\frac{1-cos\nu}{1+e} - \frac{v_{\rm r}}{V_{\rm q}}sin\nu + \frac{v_{\rm b}}{V_{\rm q}}\frac{(1-cos\nu)(2+e+ecos\nu)}{1+ecos\nu} \quad (2)$$

where e is the excentricity, $V_{\rm q}$ the velocity of the comet at perihelion, ν is the angle the radius vector makes with perihelion, or anomaly. Radiation pressure is taken into account by the parameter β, the ratio of that force to the gravitational force due to the Sun. $v_{\rm r}$ and $v_{\rm b}$ are the ejection velocities of the particle in the radial direction (outward possitive) and perpendicular to the radius vector (positive in the direction of motion of the comet). β is related to the density, ρ, and particle diameter, d, through

$$\beta = Q_{\rm rp}\frac{1.14\ 10^-4}{\rho d} \quad (3)$$

where ρ is the particle mass density (assumed to be $1gm/cm^3$). $Q_{\rm rp}$ is the radiation pressure efficiency factor (assumed to be unity).

With Eq. (1) and (2) providing the orbital elements, it is possible to determine the position of the particles at any time. We checked our calculation by first reproducing results by McIntosh (1973) and Yeomans (1981).

For $v_{\rm r}$ we have selected the values given by Mukai et al. (1985) based on a calibration of comet Halley. At $r = 1AU$, $v_{\rm r} = -4$ m/sec. For $v_{\rm b}$ we took the value of -1 m/sec, typical of a comet nucleus of 5 Km diameter, with a rotational period of around 10 hours. These values may seem too small, but Sykes et al. (1990, 1992) have found also small velocities of around 3.5 m/sec for particles of comet Tempel 2 dust trail. And for a sample of dust trails of seven periodic comets they found velocities between 2.2 and 5.2 m/sec. *Thus our values are reasonable.*

Fig. 2 shows the result of our calculation for several values of β. Other authors have drawn similar figures to Fig. 2, in particular Wu and Williams (1995) for the Draconid storm. Their curves for a similar ejection process (in terms of direction) are very similar to ours in shape. It is found that particles in quadrant II have been expelled from the nucleus *before* perihelion. Using the magnitude of the comet provided by the International Comet Quarterly Archive (Green, 1998), it is possible to construct the light curve before perihelion. It can be seen that at an anomaly of $\nu = 270$ the comet is still far from the sun inbound, and the magnitude (and thus the sublimation and dust production) is still increasing until all of them reach a maximum at perihelion ($\nu = 360$). Thus $270 < \nu < 360$ constrains the models, and in practice we find that the β that fits Fig. 1 is restricted to values $0.0001 < \beta < 0.0002$.

In Fig. 2 we plot several models for the trajectories of particles emitted by the comet for our adopted values of $v_{\rm r}$ and v_b. We see that the curves are degenerate in β and ν, in that a change in one of these parameters can be compensated by a change in the other to provide a virtually unchanged trajectory. The position along the trayectory corresponds to differente ejection times. The particles placed around the year 2000 have been emitted 12 returns ago, or 396 years ago.

The two most intense Leonid storms both have positions close to a single trajectory. We interpret this to mean that the majority of meteoroid ejected from the comet have similar ejection parameters. *This then provides the theoretical justification for the existence of the ridge identified empirically in Fig. 1.* Thus an independent restriction of the models can be made using the 100 K and 150 K points. Interestingly the same result is found for β, as can be seen from this figure.

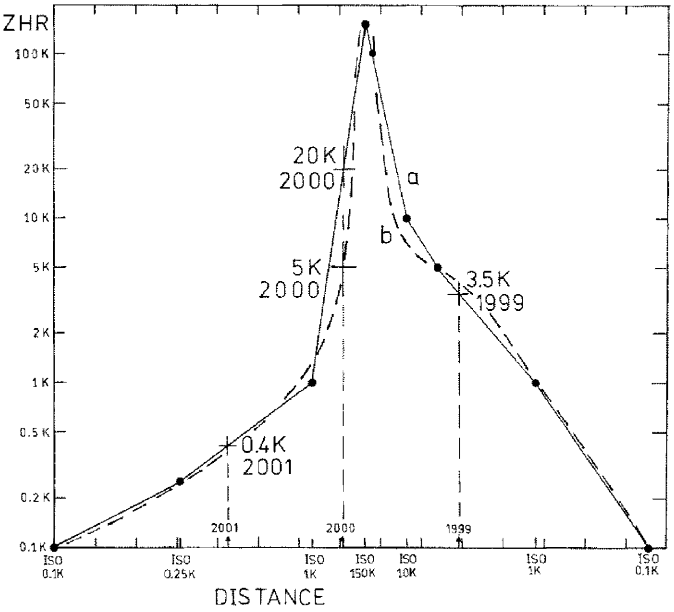

Fig. 3. Profile of the shower along the line joining the the position of the Earth for the current period (see Fig. 1). This figure allows a prediction of the shower intensity in the coming years. For 1999 the prediction is quite precise. For the year 2000 we have two solutions depending on the (unknown) particle distribution. Two such distributions are shown, a) and b), producing a ZHR between 5 K and 20 K. For 2001 again the prediction is quite precise. The distribution is asymmetric due to solar radiation pressure blowing small particles to the right. Thus large particles tend to be concentrated to the left side, while small particles should be more abundant to the right.

Using Eq. (3) these β correspond to particle diameters of 1.1 to 0.57 cms. *These values support our identification of the ridge with dust trails,* since dust trails are made of large particles and Sykes et al. (1990, 1992) found particle diameters of 0.55 cm for the dust trail of comet Tempel 2. Such large particles will yield bright meteors, as were seen in 1833 and 1966.

4. Predictions: intensity

In Fig. 3 we plot the ZHR for each isoline from Fig. 1 as a function of position along the line joining the position of the Earth during the current period (1995–2001). On our logarithmic scale, the ridge appears as a high peak. By connecting the points with line segments, we are assuming that the meteoroid density falls off exponentially with distance from the ridge. The distribution is asymmetric about the ridge and we understand why. Solar radiation pressure blows particles from left to right on this diagram, and is most intense for small particles (see Eq. 3). Thus small particles tend to dominate the right side of the diagram, while large particles tend to be concentrated toward the left side. This has an observable effect. We predict that along the years (and probably peaking at the year 2000), Leonids showers should have a tendency to have brighter meteors.

Fig. 3 will also allow us to make predictions of the shower intensity in the period 1999–2001 *by interpolation*.

In 1999 the Earth will pass very near to the point labeled $5\ K$, and thus a linear interpolation, gives a prediction of ZHR=3.5 K ±1 K. This interpolation is rather good.

For the year 2000, the trayectory that crosses over the $150\ K$ point misses the Earth by 85 days (Fig. 2). It seems that the Earth will miss the ridge of the shower both in 1999 and 2000. However for the year 2000 we have two possible solutions depending on the (unknown) particle density distribution. Two such distributions are shown in Fig. 3, originating a ZHR between 5 K and 20 K.

For 2001 again the prediction is quite precise and it will reach to a level of only 400±150.

But note that the observed values may be much smaller that these ZHRs, because of the comment made in Sect. 2, concerning the fact that ZHR is not an observed quantity.

5. Predictions: date and time

In the above data set there is no clue concerning the hour at which the shower will take place. This prediction can be made from information provided by IMO, the International Meteor Organization (Arlt, 1998). They provide the ZHR vs Solar Longitude, for $1996, 1997$ and 1998. These plots appear in our Fig. 4, and show the existence of three peaks, A, B, and C. The faintest peak(A) with ZHR of around 30 appears at a solar longitude of 236.80, and is present only in the 1996 data set and faintly in 1997. There is no trace of it in 1998. The second peak(B) with ZHR of 87–125 and solar longitude 235.17–235.39 is present for the three years. However the most intense peak(C) at ZHR of 260 and longitude 234.56 is new and is only present in the 1998 data set.

From Fig. 4 we reach two conclusions. (1) *The particle distribution is far from uniform and comes in layers*. Since peak C is the most intense and the wider of the three, it will be used for the time prediction. Converting its solar longitude to time we find a date for 1999 of November 17th at 8h 48m UT. The FWHM is 16.0 hours. These layers may eventually be related to a combination of jets with rotation of the comet. Since dust is only ejected in the day side of the nucleus, the rotating jets produce a half helix in space. Transversing this helix may produce the observed layers. (2) *There is a tendency for the peaks to get active at lower solar longitudes (earlier times)*. So it remains to be seen if peak C stays in place in 1999 or if a new peak D appears at lower longitudes in the coming years. If it does stay, then the Earth will cross it in the year 2000, on November 17th, at 14h 42m UT.

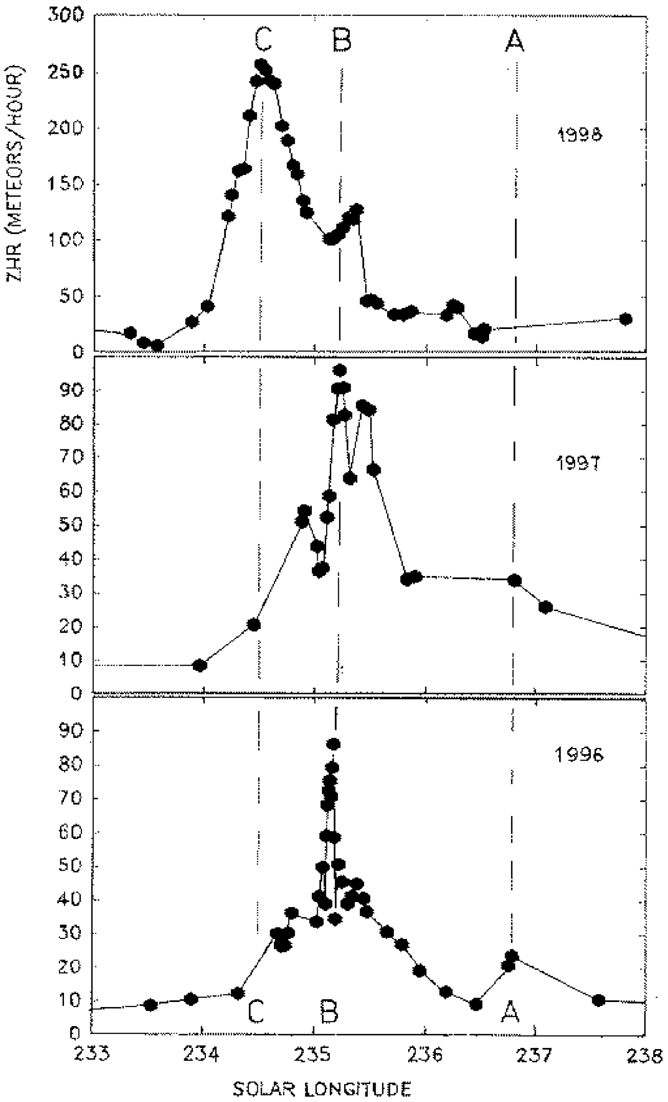

Fig. 4. ZHR vs Solar Longitude for 1996, 1997 and 1998. Notice the existence of three peaks at solar longitudes of $C = 234.56, B = 235.23, A = 236.80$. Peak C is new and was not there the previous years. Peak A has dissappeared or has become insignificant in 1998.

6. Conclusions

1. Our method of prediction is based on a plot of ΔT vs P-E (Fig. 1) and labels the points with the intensity of the shower, not the year, thus creating a map of the particle distribution around the comet. Since this procedure is not restricted to the Leonids, it can actually be applied to any other shower and thus constitutes a method of meteor storm forecasting.
2. Fig. 1 shows the existence of a "ridge" or "ribbon", a region of enhanced number of particles. We have identified this ridge with the dust trails behind periodic comets found by Sykes et al. (1990, 1992).
3. Application of our method to the Leonids allows a prediction of ZHRs for $1999, 2000, 2001$ of 3.5 K±1 K, $5\,K < ZHR < 20\,K$, and $0.4\,K$±0.1 K.
4. We predict that along the years, and probably peaking at the year 2000, showers will have a tendency to exhibit brighter meteors (see Fig. 3).

Acknowledgements. To Bradley Schaefer of Yale University, and to an unknown referee for suggestions that improved a draft of this paper. To the Council for Scientific and Technological Development of the University of the Andes, for their support.

References

Arlt R., 1998, International Meteor Organization Web Site, www.imo.net.

Beech M., Brown P., Jones J., Webster, 1997, Adv. Space Res. 20, No. 8, 1509

Brown P., Jones J., 1993, in: Meteoroids and Their Parent Bodies, eds. J. Stohl and I. P. Williams, Slovak Acad. Bratislava, p. 57

Davies J., Lovell A., 1955, MNRAS 105, p. 23

Green D. W. E., 1998. The International Comet Quarterly Archive, Smithsonian Astrophysical Observatory, available in 1998 issues of the printed ICQ.

Mason J., 1995, J. Br. Astron. Assoc. 105, 5.

McIntosh B., 1973, in: Evolutionary and Physical Properties of Meteoroids, IAU Colloquium 13, eds. C. Hemenway, P. Millman, A. Cook, NASA SP-319, p. 193

Mukai T., Mukai S., Fechtig H., Grun E., Giese R., 1985, Adv. Space Res. 5, p. 339

Rao J., 1998, Sky and Telescope 95, p. 38

Sykes M., Lien D., Walker R., 1990, Icarus 86, p. 326

Sykes M., Walker R., 1992, Icarus 95, p. 180

Yeomans D. K., 1981, Icarus 47, p. 492

Yeomans D. K., Yau K.K., Weisman P.R., et al., 1996, Icarus 124, p. 407

Wu Z., Williams I., 1992, in: Asteroids, Comets, Meteors 1991, Lunar and Planetary Institute, Houston, p. 661

Wu Z., Williams I., 1995, Plan. Space Sci. 43, 723

Wu Z., Williams I., 1996 MNRAS 280, p. 1210

Zvolankova J., 1983, Bull. Astron. Inst. Czechosl. 34, p. 122