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The anomalous dust tail of comet P/Tempel 2

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Summary. The narrow dust tail of comet P/Tempel 2, observed by *IRAS*, is the result of low-velocity emissions of large particles. Dynamical analysis of the dust particles under the influence of solar radiation pressure indicates that some of these emissions must have occurred at least 1500 days prior to the *IRAS* observations.

1 Introduction

One of the unexpected discoveries of the *IRAS* mission was the infrared dust tail trailing the periodic comet Tempel 2 (Davies *et al.* 1984). It was unusual that the tail was not seen in the visible, although a similar occurrence had been found for comet *IRAS*-Araki-Alcock (Walker *et al.* 1984). Most remarkable, perhaps, was the extreme narrowness of the tail, with a length-to-width ratio of approximately 200 to 1. The analysis of type II dust tails has up to now been understood in terms of variable dust emission from various sized particles under the influence of solar radiation pressure, giving rise to relatively broad sweeping features. Narrow tails are normally only seen in the type I plasma tails under the influence of the solar wind.

The 1983 apparition of Tempel 2 was widely observed by amateurs (Bortle 1984), and the light curve showed linear increases to and decreases from maximum light, with at least one outburst which was seen 95 days after perihelion. In 1978 at the previous perihelion passage the comet was not observed, being behind the Sun. The comet was, however, studied on its outward leg when it was approximately 3 AU from the Sun. Spinrad, Stauffer & Newburn (1979) reported that on two occasions no coma was observed. Johnson, Smith & Shorthill (1981) observed an outburst of approximately 1 mag in between the observations of Spinrad *et al.* Barker & Rybski (1980) reported another outburst in 1979 January, and brightness surges have also been seen at other apparitions. From observations of the fan-like coma features from past apparitions, Sekanina (1979) has found that approximately 120 days after perihelion, when the comet's intrinsic brightness has declined, the fan orientation can only be explained by slowly accelerated particles from 'old' emissions.

2 *IRAS* detection of the Tempel 2 tail

The *IRAS* scan strategy meant that the detection of the full extent of the Tempel 2 tail was not obtained as a snapshot, but was built up over a number of days, between 1983 July 12–18.

The complete tail was 'weeks confirmed' some ten days later. Although the processing identified the tail as many point sources, Davies *et al.* (1984) note that from examination of the raw data scans the tail was in fact continuous and close to the limit of detection. At the time of discovery the Earth was close to the orbital plane of the comet, and passed through the plane during the confirmation detection on 1983 July 22.

The position of the tail, assuming it to be the plane of the comet orbit, can be found by transforming the sky coordinates (right ascension and declination) into cometocentric coordinates using the equations defined by Finson & Probstein (1968a, appendix B). The cometocentric coordinate system is defined as having the comet nucleus at the origin, and an axis ξ pointing radially away from the Sun. An orthogonal axis η points in the direction opposite to the comets motion. A third axis ζ measures distance from the orbit plane, forming a right-hand set.

In Fig. 1 are plotted the positions of the tail elements from Davies *et al.* (1984) for the first set of *IRAS* detections in these cometocentric coordinates, assuming the tail lies in the orbit plane (i.e. $\zeta = 0$). The position of the Sun and Earth in these coordinates for the date JD 2445530.0 (1983 July 14) are $\xi_\odot = -1.458$, $\eta_\odot = 0$, $\zeta_\odot = 0$ and $\xi_\oplus = -0.805$, $\eta_\oplus = 0.780$, $\zeta_\oplus = -0.031$ AU respectively, with the ζ-axis pointing out of the page in Fig. 1. Although the Earth was close to the orbit plane, the scatter on the points after transformation is quite small and the tail still appears as a very narrow feature. This implies that the narrowness of the tail as seen on the sky is not due to viewing, almost edge-on, dust spread out in the orbit plane. This conclusion was confirmed by repeating the transformation for the second and third set of tail positions given by Davies *et al.* (1984). During the second set the Earth passed through the comet orbit plane, and the third set was seen from the opposite side as the first set, and yet the derived cometocentric coordinates still show a very narrow tail at the same position angle with respect to the nucleus.

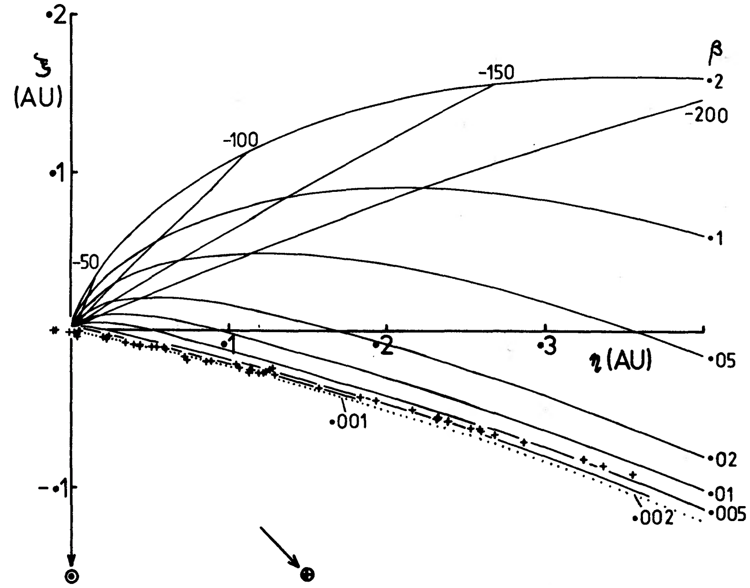

Figure 1. The crosses indicate the observed tail elements of comet Tempel 2 in the plane of the orbit. The curved lines show the syndynes for a range of values of β from 0.2 to 0.001. The synchrones are shown for release dates 50, 100, 150 and 200 days prior to the observation, further synchrones have been omitted for the sake of clarity. The orbital path of the comet is indicated by the dotted line. The direction of the Earth at the time of the observation is also indicated.

3 The tail

The dynamical analysis of cometary dust tails, as defined by Finson & Probstein (1968a), uses integration of syndynes or synchrones to match the observed dust distribution with a model. For a given time of observation (a snapshot) a syndyne is defined as the locus, in cometocentric coordinates, of similar sized particles (rigorously particles experiencing the same accelerative force due to radiation pressure) released from the nucleus with zero initial relative velocity at different times in the past. A synchrone is defined as the locus, in cometocentric coordinates, of different sized particles having the same release date. As discussed by Finson & Probstein (1968a) syndynes appear as curves, emanating from the origin in a direction radially away from the Sun. Synchrones appear almost as straight lines having initial tail angles significantly non-radial, and whose position angle increases with increasing time since release.

Fig. 1 shows the syndynes and synchrones for comet Tempel 2 on the date JD 2445530.0. The theoretical dust orbits are calculated using Keplerian orbit theory for dust particles experiencing a reduced gravitational force, where β defines the ratio of the radiation pressure to gravitational forces. The dimensionless parameter β is given by Sekanina (1980)

$$\beta = 0.585 \times 10^{-3} \times Q_{\mathrm{pr}}/(\rho \times a)\ \mathrm{kg\ m^{-2}}$$

where Q_{pr} is the integrated efficiency factor for radiation pressure, ρ is the particle density ($\mathrm{kg\ m^{-3}}$) and a is the particle radius (m). The value of β is inversely proportional to the particle size and density, thus the smaller or less dense particles are blown furthest and most quickly away from the nucleus. In Fig. 1 are plotted the syndynes for a range of values of β from 0.2 to 0.001. Also plotted are the synchrones for release dates 50, 100, 150 and 200 days prior to the observation. For the slowest moving particles ($\beta = 0.001$ and 0.002) the syndynes have been terminated for release dates 2000 days prior to observation (~ 1 orbital period).

It can be seen from Fig. 1 that for very small values of β the syndynes crowd closely together and become parallel to the orbital path of the comet. This is because a small increase in the radial distance, due to radiation pressure, will result in a significant orbital lag over long periods. For very large particles and infinite time, the syndynes (for zero initial relative velocity) will lie along the orbital path. The position angle of this limiting case will clearly depend on the position of the comet in its orbit, and on the orbital eccentricity.

In this limiting direction, since the syndynes for these slow-moving particles are parallel to each other, then the synchrones must also lie in the same direction. This means that it is impossible to distinguish between particle size/density and time of release for grains lying along this line.

Fig. 1 shows that the positions of the tail elements seen by *IRAS* are coincident with this large particle asymptote. In principle a narrow tail could be formed by ejection in one direction only, but no sensible mechanism would explain the orientation of the observed tail by this means. Hence the particles must have small accelerations and result from 'old' emissions. The extreme tail element has $\beta < 0.01$ and calculations of the synchrones show that it would take a minimum of 1500 days (3/4 of an orbital period) to reach its present position. As the *IRAS* picture of the tail was not a snapshot, but built up over a number of days, the syndynes should rigorously be calculated for each separate observation; however the change in position of the syndynes for the extreme tail element from that plotted is only 0.005 AU, but this will account in part for some of the shift of the extreme tail elements away from the asymptote.

For reasonable values of the radiation pressure efficiency ($Q_{\mathrm{pr}} \sim 1$) and for the density it can be seen that the particles making up the tail must be in the sub-millimetre range. If these particles have low albedos this could explain the lack of a visible counterpart to the tail seen in the 25-μm *IRAS* band. It should be noted that very small sub-μm particles can have very low values for β (Hanner 1980; Eaton 1984), and exhibit very inefficient visible scattering, but there is no way that such particles could emit efficiently at 25 μm.

An important question that arises is how can such a tail, part of which is at least 1500 days old, keep its narrowness and form over such lengths of time. The syndynes are normally calculated for zero initial relative velocity and any emission velocities are modelled as spherically-symmetric shells expanding their size with time along the syndyne (Finson & Probstein 1968a). The narrowness of the tail (~4 arcmin, Davies *et al.* 1984) puts an upper limit on the velocity dispersion of the particles. Assuming the particles were released at least 1500 days prior to observation, the maximum velocity dispersion must be less than $2\,\mathrm{m\,s^{-1}}$ to preserve the narrowness of the tail. This velocity is of the order of the escape velocity from a 1.6-km radius cometary nucleus (Spinrad *et al.* 1979), and is much less than has been used to model comet dust tails (Finson & Probstein 1968b) or meteor streams (Fox, Williams & Hughes 1983).

The Poynting–Robertson effect will be negligible for these large particles for time-scales of the order of one or two orbital revolutions. Burns & Soter (1980) suggest that a particle orbit will collapse due to the Poynting–Robertson effect in a characteristic time approximately equal to that in which the particle interacts with its own equivalent mass in radiation. For sub-millimetre particles in Tempel 2's orbit, this characteristic time is 10^5–10^6 orbital revolutions.

To estimate the possible effect of Jupiter on the stability of the tail, the relative positions of Jupiter and the comet were calculated for one cometary orbit between the 1978 and 1983 perihelions. The largest tidal perturbation between the comet and the extreme end of the observed tail (0.4 AU from the nucleus) would have occurred around JD 2444200 when the comet was 4.3 AU from the Sun, made its closest approach to Jupiter (3.3 AU) and the tail was pointing approximately away from Jupiter. The tidal effect of Jupiter between the nucleus (3.3 AU distant) and tail (~3.7 AU distant) would have been $\sim 0.02\,GM_{♃}$. The ratio of Jupiter's gravitational force to the Sun's at the comet nucleus is only ~0.002. The tidal perturbation is therefore much less than the smallest radiative acceleration considered here ($\beta = 0.001$).

The tail of Tempel 2 appears then to be stable against perturbing forces over periods of at least a few orbital revolutions. The surprising result for the long-term existence of this narrow feature is the extremely low-velocity dispersion of the constituent particles, although Sekanina (1979) hinted at the existence of slow-moving particles. These low-velocity outbursts may be associated with activity at large heliocentric distances, such as that seen by Johnson *et al.* (1981).

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