

THE SPLIT TAIL OF COMET SEKI-LINES

BRUNO J. JAMBOR*

Martin Marietta Aerospace, Denver, Colorado

Received 1973 April 16; revised 1973 May 31

ABSTRACT

Comet Seki-Lines was analyzed using a method previously applied to comet Arend-Roland. The split tail is a dust tail which resulted from the combination of a sudden increase of grain production and fast melting near perihelion. A suggestion is made for the origin of split tails in other comets.

Subject headings: comets — interplanetary medium

I. INTRODUCTION

Comet Seki-Lines (1962c) is a member of a remarkable group of comets which show a split tail. It also was a Sun grazer with a perihelion distance of just under 7 solar radii. It was discovered on 1962 February 4 by R. D. Lines and T. Seki.

II. OBSERVATIONAL MATERIAL

A series of remarkable plates was taken by F. D. Miller, using the 24-36-inch (61-91-cm) Curtis-Schmidt telescope of the University of Michigan. A combination of IIa-E "red" plates and RG1 Schott filter gives a transmission range from 610 $m\mu$ to about 700 $m\mu$. This feature very nearly eliminates molecular and atomic emissions in the comet tail, the only exception being possibly some light from the forbidden [O I] $^3P-^1D$ emission band in the 630-636- $m\mu$ range whose presence has been reported by Arpigny (1965). It is, however, safe to say that such contamination can be only of minimal consequence and that most of the light is reflected by solid grains. These filtered plates were taken about 15 days after perihelion and show the tail split into two almost equal parts by a zone which, at first sight, looks like a shadow. This shadow zone appears at about 1.5×10^5 km from the nucleus and extends about 10^6 km into the tail. The shadow zone is slightly behind the anti-Sun axis through the comet nucleus, in the direction opposite to the comet's motion. The plates were standardized with a 14-spot Weston tube sensitometer, allowing relative photometry to be done readily. On the nights the plates were taken, the Moon was quite bright and limited the effectiveness of long exposures. All plates were taken in focus and guided. The short focal length of the telescope does not allow one to make attempts at absolute photometry using the spread-out light of the stars as absolute standards, as out-of-focus plates would. It is felt that methods using the absolute brightness of the sky background would have been too inaccurate in our case. The plates were analyzed with a microdensitometer, and the region of the comet was mapped to show isophotes.

III. THE SPLIT TAIL: POSSIBLE EXPLANATIONS

The simplest idea would be to assume that the shadow is created by the nucleus. However, the geometrical shadow created by a nucleus of radius 1 km at 1 a.u. from the Sun is only about 200 km in extent, lies directly in the line Sun-nucleus, and

* This work is taken from a thesis submitted to the Graduate College, University of Illinois, 1973.

becomes narrower as it recedes from the Sun. In any case such a shadow would be below the resolution limit imposed by seeing. So, even if the nucleus is much larger (10 km), we could not detect the shadow without great difficulty.

A more sophisticated idea is a possible extinction effect due to the conglomeration of dust grains in the coma region. Assuming a Whipple model for the nucleus (Whipple 1951, 1963), we can calculate the number of grains ejected from such a nucleus. The extinction due to grains $1\ \mu$ in size ejected with velocity $0.3\ \text{km s}^{-1}$ from a nucleus of radius 5 km is practically nil (Jambor 1973). If we increase the production rate by a factor of 10 as compared to the normal rate, extinction effects can be detected only in the immediate vicinity of the nucleus, for distances of less than 6 km, which may be less than the radius of the nucleus itself. So extinction by dust grains cannot explain the tail of Seki-Lines.

The last explanation involves mapping the region of the tail in terms of synchrones and syndynes following the method of Finson and Probst (1968) and calculating the relative brightness at each point. A shadow can be created by diminishing the production rate of dust grains at times close to perihelion passage. The shadow is then due to a number of "missing synchrones." The physical reasons will be explained shortly.

IV. THE FINSON AND PROBST METHOD

The Finson and Probst (1968) method is based on a model of the acceleration of dust grains by interaction with the gas developed by Probst (1969). In short, the gases are assumed to expand with spherical symmetry and the dust grains are released with zero velocity relative to the nucleus. Due to hydrodynamic interaction between the dust and the gas in the coma region, the dust reaches a final velocity of around $0.4\ \text{km s}^{-1}$, within 20 radii of the nucleus. This region then behaves like a point source with respect to the tail. From that point on, the action of solar radiation pressure and solar gravitation takes over. A dust grain released from a comet with a parabolic orbit will have a hyperbolic orbit due to the outward acceleration of radiation pressure. The grains will move in a weakened gravitational field, and one can calculate their position depending on the time elapsed since release, τ , and their relative size, described by a

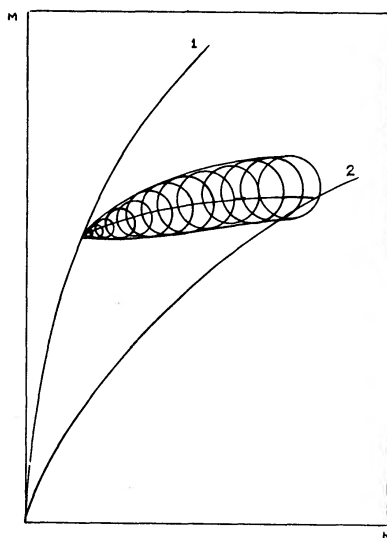


FIG. 1.—A cut through a dust tail, showing the appearance under the combined effects of spherical expansion and motion in a weakened gravitational field. The curve marked 1 is synchrone corresponding to recent release times of the dust; curve 2 is the longest time since release considered.

parameter, $1 - \mu$, which measures the ratio of the forces of radiation pressure and gravity. Given a certain time of release and a spread in size, the locus in time is called a synchronone. Similarly for a given size and different times we obtain the syndynes. The tail of the comet is then considered to be a collection of synchronones or syndynes. Taking the synchronone approach, for example, one can calculate the earliest and latest times of significant contribution to the dust tail as seen on a particular day. Combining the motion in space, in the gravitational field weakened by radiation pressure, and the initial acceleration by the gas which creates spherical expansion, the grains are moving along hyperbolic paths and expanding spherically with the radius of the sphere being at each instant equal to the product of the velocity of expansion (about 0.4 km s^{-1}) and the time elapsed since release from the nucleus. Figure 1 shows what the tail looks like under these assumptions. The latest synchronone (short time) carries small spheres; the earliest one (long time), much larger spheres. The tail has a leading edge with little dispersion and mixture of sizes of grains, and a much broader, diffuse trailing region, made up of grains of different sizes released at different times.

To calculate the brightness at any point in the tail, one finds what spread in time (synchronones) and in sizes (syndynes) contributes to the scattered brightness and performs a double integration over time and size.

V. THE RELATIVE BRIGHTNESS

The calculation of the density of dust grains at one point, which determines the brightness, as described by Finson and Probstein (1968), involves three parameters. The size distribution function, $f(1 - \mu)$, is weighted by the light scattering ability. The form of the distribution function was chosen to be a zeroth-order logarithmic distribution (Kerker 1969). This distribution is derived from the normal distribution by making the restrictions that the sizes cannot be negative and the distribution is skewed. Its expression is:

$$p(a) = \frac{\exp [-(\log a - \log a_M)^2 / 2\sigma_0^2]}{(2\pi)^{1/2} \sigma_0 a_M \exp (\sigma_0^2 / 2)},$$

where a is the size, a_M is the modal or most common size, and σ_0 measures the width and skewness of the distribution. Such a distribution allows us to determine the value of the maximum frequency or modal value, and the width or skewness of the distribution σ_0 , with a good precision. The relative dust emission rate $\dot{N}_d(\tau)$ and the particle velocity function v are the two other parameters. The last one depends both on the size parameter $1 - \mu$ and the time τ : $v(1 - \mu, \tau)$. The judicious choice of these three parameters allows us to obtain a good match between the measured and the calculated isophotes as shown in figure 2. The two portions of the tail are seen clearly with a dip in the shadow region. This region corresponds to synchronones very close to perihelion, as can be seen in figure 2 where the perihelion synchronone has also been drawn. The calculated isophotes approximate the measured ones fairly well in the mid portions of the tail. The agreement is only marginally closer to the nucleus. However, in these regions, at distances of only $2 \times 10^5 \text{ km}$, we are very close to the coma, and the hypersonic approximation introduced by Finson and Probstein (1968) to compute brightness distribution in the tail may be breaking down. The synchronones are piling up very close together and contributions from many of these tend to raise the calculated brightness. The parameters chosen to obtain this fit are shown in figures 3, 4, and 5. The final velocity parameter $v(1 - \mu, \tau)$ is shown in both its time and size dependence. We have retained values very similar to those which emerged from the study of Probstein (1969). The velocity parameter mainly affects the size of the expanding sphere or radius $v(1 - \mu, \tau)\tau$ and determines the zone of influence of each synchronone.

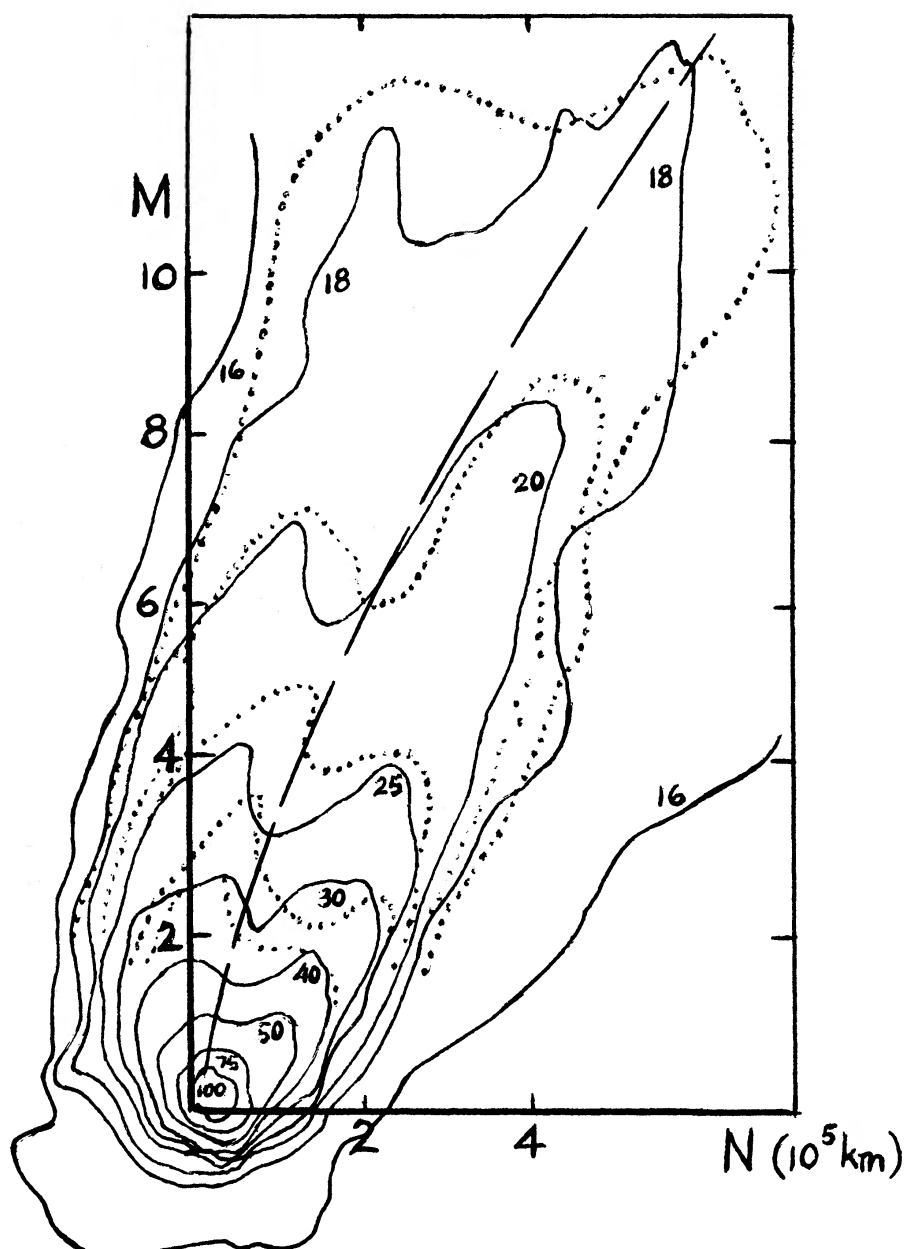


FIG. 2.—Isophotes of Comet Seki-Lines. The M -axis is radially away from the Sun. *Full lines*, the measured isophotes; *dashed lines*, the calculated ones. The long dashed curve is the perihelion synchrone.

The size distribution $f(1 - \mu)$ is a zeroth-order logarithmic distribution. The peak value strongly emphasizes the importance of larger grains. Since the scattering ability of the large grains is less than that of smaller grains, more of them are needed to match the contribution to brightness of the small grains. The relative rate of dust emission N_d shows a strong peak close to perihelion and a sudden decrease to nearly zero value and a slow rise to a rather low final value. This parameter is strongly influenced by the physics of the nucleus. Comet Seki-Lines approached the Sun very quickly, grazing the corona, then receded just as quickly on a parabolic path. This suggests a rather sudden

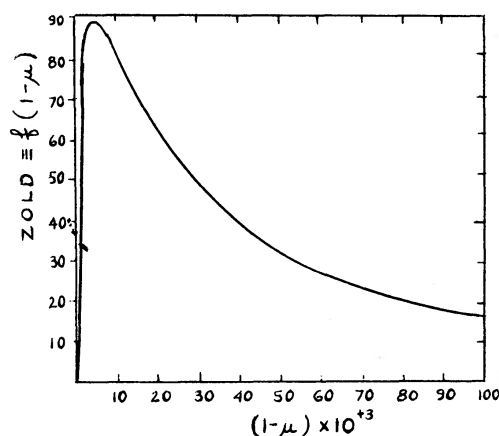


FIG. 3.—The size distribution function $f(1 - \mu)$ weighted by the light scattering ability of the dust grains. It is a zeroth-order logarithmic distribution with maximum frequency $(1 - \mu)_{\max} = 0.005$ and skewness $\sigma_0 = 0.7$.

heating and melting rate close to the Sun and thus a sudden increase in dust particle emission. Huebner (1970) has shown that an increase in dust production and release of large grains and quick melting is to be expected. For materials of interest to comets, the dust component will have a latent heat of vaporization ranging from $L = 20$ to about 100 kcal per mole. Huebner shows that for this range of L , the evaporation rate increases very fast as the distance from the Sun decreases. For $L = 30$ kcal per mole, for example, the rate of evaporation Z_d varies from $Z_d = 10^{12}$ [molecules $\text{cm}^{-2} \text{s}^{-1}$ sterad $^{-1}$] at 0.5 a.u. to $Z_d = 10^{20}$ at 0.05 a.u. The increase is faster the larger the value of the latent heat of evaporation. This means that dust particles will suddenly start to vaporize at short solar distances. For an extreme case, like the Sun-grazing comet Ikeya-Seki, Huebner calculates that ironlike grains of size $\sim 2 \times 10^{-5}$ cm will survive only about 3 minutes at 0.02 a.u. There will be no dust tail then. The chosen values of $\dot{N}_d(t)$ show this phenomenon clearly. An increase in the dust emission rate at perihelion by a factor of 45 compared to earlier values is followed by a sudden decrease to a value close to zero and a slow increase to a final value only one-ninetieth of the peak value. The duration of the increase to peak value at perihelion is about 13 hours; that of the decrease is some 11 hours. The duration of the near-zero release is 5 hours. The reason

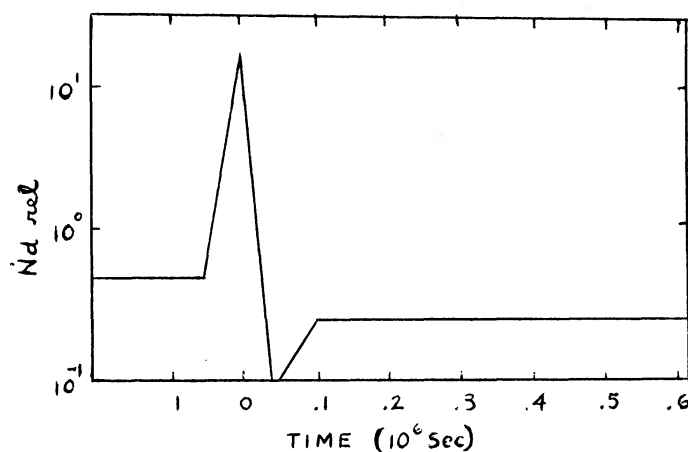
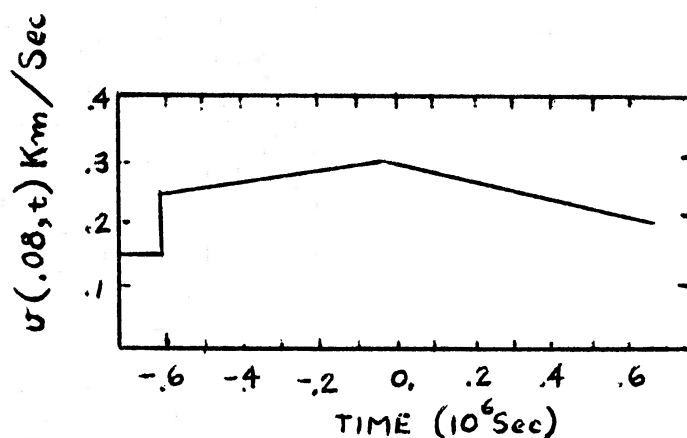
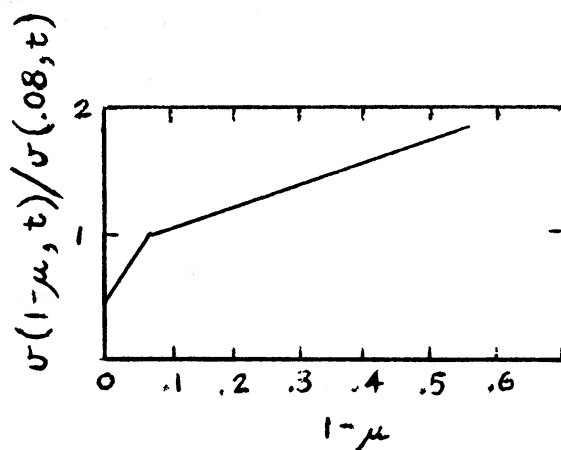


FIG. 4.—The relative dust emission rate as a function of time. Time zero is perihelion, negative time is before and positive time after perihelion.



a)



b)

FIG. 5.—The final velocity of the dust after interaction with gas in the coma: (a) time dependence, (b) size dependence.

for the decrease is understandable: the nucleus recedes from the Sun quickly. The decrease to a nearly zero value, however, is a sign that a strong melting effect, evaporating the small grains and reducing the size of the very large ones quickly, is following soon after perihelion passage, with a time lapse of a few hours. The 5 hours during which very little dust is produced means that any dust of size sufficiently small to scatter light efficiently is melted quickly and evaporated. In essence there is no production of a dust tail for a few hours. Only a gaseous tail can be seen then.

The two most crucial parameters controlling the relative brightness in the tail are the size distribution $f(1 - \mu)$ and the rate of dust emission $\dot{N}_d(t)$. Since the tail of Seki-Lines was made up of two parts, one formed before perihelion and containing larger grains and one formed after perihelion containing smaller grains, and since the brightness of both parts was about the same, the size distribution, weighted by the light scattering ability, has to favor the larger grains. The scatter or skewness of the distribution in turn controls the rate of fall-off of the brightness with distance from the nucleus. The rate of dust emission $\dot{N}_d(t)$ strongly controls the density gradient from one side of the tail to the other. The choices among the three parameters are not

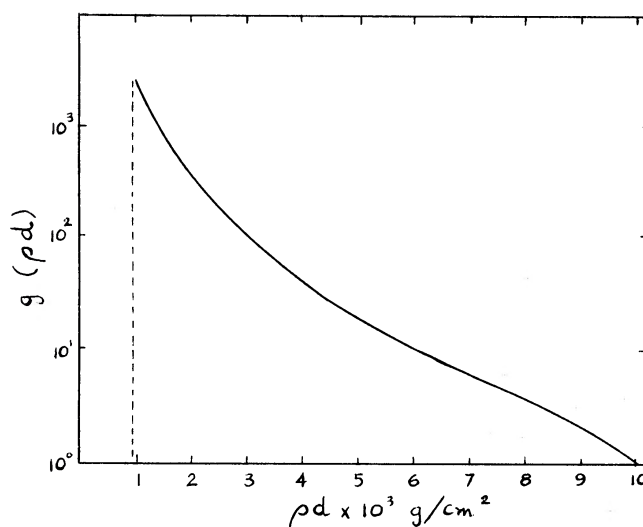


FIG. 6.—The size distribution of the dust grains as a function of the product of the density ρ and the diameter d of the dust.

infinite in number. The choice of $v(1 - \mu, t)$ has to follow some reasonable model of dust flow near the coma. The size distribution is restricted by the apparent extent of the tail and the dynamics of the particles. The brightness, in turn, is so extremely sensitive to the rate of dust emission that even minute departures from the best model gives substantially different results. It seems certain that this parameter is the most accurately determinable one of the three.

To get the physical size distribution, one removes the effect of light scattering ability from $f(1 - \mu)$ and obtains a distribution as a function of the diameter of the grains and their density. This function $g(\rho_d d)$ is shown in figure 6. The root mean square value of the distribution is $2.65 \times 10^{-3} \text{ g cm}^{-2}$. This gives an rms value of 14μ for the radius if we take $\rho_d = 1 \text{ g cm}^{-3}$, 7μ for 2 g cm^{-3} , and 2μ for 7 g cm^{-3} .

VI. DISCUSSION

The Finson and Probst method has been applied first, with success, to Comet Arend-Roland (Finson and Probst 1968). Recently, Sekanina and Miller (1973) have applied it to Comet Bennett. Seki-Lines, however, is the most crucial test yet, due to the fact that the tail has a very striking feature and the nucleus passed so close to the Sun.

Comet Seki-Lines is not unique in showing a split tail. Other comets such as Donati (1858), as drawn by G. P. Bond on October 10 of that year, and Tago-Sato-Kosaka (1969) have shown similar phenomena. It does not appear that a split tail is limited exclusively to Sun grazers. Donati's comet, for example, had a perihelion distance of 0.58 a.u. On the other hand, Comet Ikeya-Seki did not show a split tail, although it came within 0.007 a.u. of the Sun. Pictures of this object were taken on 1965 October 30, nine days after perihelion, and were presented by Brandt (1968) as an example of a tail which is definitely of type II. However, all portions of the visible tail on that date correspond to emission times subsequent to perihelion. All the synchroes which represent pre-perihelion and perihelion emission have disappeared. The grains have probably all melted; and if there was a split tail, it was not positioned near the tail visible on 1965 October 30.

To analyze split tails, the first necessity is therefore to obtain good plates using the right types of filters to separate plasma and dust tails. Comet Seki-Lines is, to our

knowledge, the first comet with a split tail to offer the possibility of being photometrically analyzed. We suggest that the split-tail phenomenon is the result of a sudden burst of dust release. Such an event will naturally happen for Sun grazers because of intense solar action; but other, more distant comets could very likely show such phenomena. Even if the perihelion distance is not very small, perihelion passage corresponds to maximum solar heating. It is not impossible that a rise in the rate of release of the dust can occur there. It is also possible that a pocket of dust is suddenly unveiled as ices melt, causing a burst of dust release. One or two such bursts can create a split tail.

I would like to thank Dr. F. D. Miller for suggesting this topic and loaning me his plates of Seki-Lines. I thank also Drs. S. P. Wyatt and K. M. Yoss for helpful discussions.

REFERENCES

- Arpigny, C. 1965, *Ann. Rev. Astr. and Ap.*, **3**, 372.
 Brandt, J. C. 1968, *Ann. Rev. Astr. and Ap.*, **6**, 284.
 Finson, M. L., and Probst, R. F. 1968, *Ap. J.*, **154**, 327.
 Huebner, W. F. 1970, *Astr. and Ap.*, **5**, 286.
 Jambor, B. J. 1973, thesis, University of Illinois.
 Kerker, M. 1969, *The Scattering of Light* (London and New York: Academic Press), chap. 7.
 Probst, R. F. 1969, *The Dusty Gasdynamics of Comet Heads* (Society for Industrial and Applied Mathematics, Philadelphia, Penn.).
 Sekania, Z., and Miller, F. D. 1973, *Science*, **179**, 565.
 Whipple, F. L. 1951, *Ap. J.*, **113**, 464.
 ———. 1963, in *The Moon, Meteorites, and Comets*, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press).

ABSTRACTS OF ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES

Supplement No. 232

MOLECULAR CONSTANTS OF THE TiO MOLECULE

JOHN G. PHILLIPS

Berkeley Astronomy Department, University of California

At present five singlet and three triplet band systems have been positively identified in the TiO spectrum. They involve six singlet and four triplet electronic states. Published analyses of the eight-band systems show that they are known with varying degrees of completeness. Molecular constants are particularly incomplete for the extensive triplet systems.

The current Berkeley measurements and analyses of TiO extend from 4000 to 9000 Å. Approximately 50,000 rotational lines have been measured in this wavelength interval. Forty-eight bands in six systems proved to be strong enough for definitive rotational analysis and the extension and improvement of corresponding molecular constants.

For the triplet systems, molecular constants have been derived from 22 bands of the α -system ($C^3\Delta-X^3\Delta$), 18 bands of the γ -system ($A^3\Phi-X^3\Delta$), and one band of the γ' -system ($B^3\Pi-X^3\Delta$). In all systems the usual interactions had to be augmented by the addition of spin-orbit and spin-spin interactions to account for "anomalous" triplet splittings. For $v' = 6$ and 7 of the $C^3\Delta$ state, rotational perturbations at low J led to such great uncertainties in the location of band origins that unique constants were unattainable. Smaller anomalies at $v' = 2$ of the $C^3\Delta$ state show that perturbations suffered by this electronic state are more widespread than previously thought. The other triplet states are more regular. For the $A^3\Delta$ state there appears to be a progressive decrease of triplet splitting with increasing v' .

For the singlet systems, our analyses of three bands of the β -system ($c'\Phi-a'\Delta$) and one band of the ($e'\Sigma-d'\Sigma$) system have been combined with results derived elsewhere into as complete a listing of molecular constants as can be compiled at the present time.