A134

2010 Oct. 2
十三夜

THE POYNTING-ROBERTSON EFFECT ON METEOR ORBITS

STANLEY P. WYATT, JR., AND FRED L. WHIPPLE

流星ノ軌道ニ対スル ポインティング−ロバートソン効果

スタンレイ P. ワイアット, ジュニア, ト フレッド L. ホイップル

Harvard College Observatory

Received June 30, 1949

ABSTRACT

The Poynting-Robertson effect will operate to sweep small particles of the solar system into the sun at a cosmically rapid rate. Robertson derived an expression for the times of fall from initially circular orbits. Since, if other parameters are equal, the times are much less for orbits of high eccentricity, tables are given here to enable simple calculation of the times of fall in terms of the initial orbital elements, q and e, and particle radius and density. Total times of collapse are computed for several meteor showers.

ポインティング−ロバートソン効果ハ 太陽系ノ 小サイ粒子ヲ 宇宙的ニ 早イ速度デ 太陽ニ掃キ落ス作用ヲ行ウ。 ロバートソンハ, 始メニ円軌道デアッタ物ノ 落下時間ノ 計算式ヲ導イタ。 モシ他ノ軌道要素ガ同ジナラバ, 大キイ離心率ノ軌道デハ 落下時間ハ小サイノデ, 始メノ軌道要素 q ト e 及ビ粒子ノ半径ト密度ニヨッテ落下時間ヲ簡単ニ計算スルコトガ出来ル表ガ ココニ与ヘラレテイル。 イクツカノ流星群ニツイテハ 衝突マデノ 全時間ガ 計算サレテイル。

Since there is a linear dependence of the time on particle radius, the material in showers should ultimately be dispersed so that larger particles move with greater orbital a and e than do the smaller ones. This leads to the possibility of observing the Poynting-Robertson effect in a given swarm by a correlation of the observed mean magnitude of meteors with the time while the earth transits the shower. Such a correlation is not detected for any shower definitively; an upper limit, therefore, is set for the age of showers, ranging from five million years for some to less than one hundred thousand years for the Geminids.

If some sporadic meteors had a common origin with the meteorites and asteroids, the operation of the Poynting-Robertson force requires that, for times of origin longer ago than the sixty million years suggested by Bauer, all material of radius less than 0.08 cm has been swept into the sun. Therefore, virtually no sporadic meteors fainter than the fifth magnitude can be arriving now on the earth unless they are cometary or interstellar in origin. For a time of three billion years the minimum radius is about 4 cm.

The tables given for computation of the times of orbital contraction are valid for any radiating body of known mass and radiation by means of a simple correction. The process of contraction is faster by a factor of about 100,000 for B stars than for the sun. But, conversely, the Poynting-Robertson effect due to the general radiation of a galaxy is entirely too small to affect appreciably the dynamics of interstellar dust.

粒子半径ト時間ノ間ニハ 線形(一次式)ノ関係ガアルノデ 流星群ニアル物質ハ 大イニ分散スルノデ, 大キイ粒子ハ小サイモノヨリモ 大キイ a ト e デ動イテイル。 コノコトカラ, 地球ガ流星群ノ中ヲ通過スル時, 流星光度ト関係スル P.-R. 効果ヲ観測スルコトガ可能トナル。 コノ様ナ関係ガ ドノ様ナ流星群ニツイテモ必ズ見ツカルトハ言エナイ。 上限ノ値ハ, 流星群ノ寿命ニ関係シテ, 例エバ双子座群ニツイテハ, 500万年カラ 数10万年ヨリ短イ年数デアル。

モシ散在流星ガ隕石ト小惑星ナドト同ジ起源ヲ持ツナラバ, P.R.効果ノ働キハ, Bauerガ示シタ様ニ 6000万(60×100万)年ヨリ 大キイ寿命ヲ持ツコトニナリ, 半径ガ 0.08 cm ヨリ小サイ物ハ 全テ 太陽ニ落チテシマウ。 実際ニ, 従ッテ 彗星起源カ又ハ恒星間空間カラノモノデナイ限リ 5等級ヨリ暗イ流星デ 地球ニ到達スル散在流星ハナイ筈デアル。 30億年(米語デハ billion = 10億)ノ寿命ニ対スル最小半径ハ 約 4 cm デアル。

軌道ノ縮小ノ時間ノ計算ノ為ニ与ヘラレタ表ハ, 質量ト輻射量ヲ簡単ニ補正スルコトニヨッテ 全テノ輻射体ニ適用デキル。 縮小ノ過程ハ B型星ニツイテハ 太陽ヨリ約10万倍モ早イ。 コレニ対シテ, 恒星間空間ノダストノ力学ニ対スル銀河ノ全輻射ニヨル P.R. 効果ハ 大イニ小サクテ殆ド影響ハナイ。

In the early part of this century, J. H. Poynting[1] considered the effects of the absorption and subsequent re-emission of sunlight by small isolated particles in the solar system. His work was later modified by H. P. Robertson,[2] who used a precise relativistic treatment to establish, once and for all, the equations of motion for such particles to terms of the first order in the ratio of the velocity of the particle to that of light. While the process of absorption and re-emission produces no net force on a particle when one chooses to work with a stationary frame referred to the particle, it is found when the solar reference frame is used that there is introduced a resisting force on the particle which is proportional to its velocity. The retarding force exhibited in the equations of motion results in a slow secular decrease in semi-major axis and eccentricity of the orbit of any small body. Ultimately the body will fall into the sun.

20世紀ノ初メニ、J. H. Poynting[1]ハ、太陽系内ノ小サイ個々ノ粒子ニヨッテ吸収サレ、ソシテ再放出サレル太陽ノ光ノ効果ニツイテ考ヘタ。

1) Phil Trans. R. Soc. London, A, 202, 525, 1903.

彼ノ研究ハ後ニ H. P. Robertson[2] ニヨッテ改良サレ、彼ハ正確ナ相対論ニヨル扱イヲシテ、粒子ノ光ニ対スル速度ノ比率ノ第1次的ナ項ヲ用イテコノ粒子ノ運動方程式ヲ確立シタ。粒子ニ準拠スル静止的座標ヲ用ルコトニシタ場合ニハ吸収ト再放射ノ過程ハ粒子ニ対シテ力ハ働カナイノデ、速度ニ比例スル抵抗力ヲ生成スルタメニハ太陽ニ準拠スル座標ヲ用イナケレバナラナイコトニ気ガツイタ。運動方程式ニ示サレル遅延力ハ微小天体ノ軌道ノ半長径ト離心率ヲユックリ永年的ニ小サクナルコトヲ示ス。ソシテ最後ニハコノ小天体ハ太陽ニ落下スル。

Inasmuch as small meteoric material must be strongly affected by the Poynting-Robertson effect, it is of interest to find a method of calculating the time necessary, under given initial conditions, for such matter to be drawn into the sun. Robertson solved the problem for initially circular orbits. Since, however, for a given semi-major axis the time of fall is substantially less for highly eccentric orbits than for circular ones, we propose to develop here a method of computing the time numerically for the general case.

The assumptions in the development are as follows: (1) that the particles are spherical, with radius s, and of uniform density, ρ; (2) that they are somewhat larger than the critical limit where radiation pressure balances gravitational attraction ($s\rho > 5.72 \times 10^{-5}$ gm/cm^2) and large enough compared with the wave length of light so that diffraction effects are not appreciable; and (3) that the particles absorb all incident radiation from the sun over a cross-section πs^2 and re-emit this radiation isotropically at the same rate.

[1] *Phil. Trans. R. Soc. London, A*, 202, 525, 1903.

[2] *M.N.*, 97, 423, 1937.

小サイ流星物質ハ P.R.効果ヲ大キク受ケルノデ、イロイロナ初期条件ノモトデ太陽ニ落ちルニ必要ナ時間ヲ計算スル方法ヲ見ツケルコトハ興味アルコトデアル。ロバートソンハ始メニ円軌道デアッタ問題ヲ解決シタ。

与ヘラレタ軌道半長径ニツイテ、落下時間ハ離心率ガ大キイ場合ハ円軌道ノ場合ヨリカナリ短イノデ、ココデハ一般ノ場合ニツイテ数値的ニ落下時間ヲ計算スル方法ヲ展開スルコトヲ提案スル。

展開ノ仮定条件ハ次ノ通リデアル：(1) 粒子ハ球状デ半径 s、一様ナ密度、ρ；(2) 放射圧ト重力ニヨル引力トツリ合ッテイル、マタハソレヨリ大キイ ($s\rho > 5.72 \times 10^{-5}$ gm/cm^2) ソシテ光ノ干渉効果ガ大キクナク光ノ波長ヨリモ充分大キイコト。(3) 粒子ハソノ断面 πs^2 デ太陽カラ受ケル輻射ヲ吸収シ、同時ニ等方的ニコノ輻射ヲ再放出モトスル。

The radial and perpendicular components of the equations of motion as found by Robertson are

$$\ddot{r} - r\dot{\theta}^2 = -\frac{\mu}{r^2} - \frac{2\alpha\dot{r}}{r^2}, \tag{1}$$

and

$$\frac{1}{r}\frac{d}{dt}(r^2\dot{\theta}) = -\frac{\alpha\dot{\theta}}{r^2}, \tag{2}$$

動 太陽質量

where $\mu = GM - \alpha c$, the usual solar gravitational constant decreased by the outward-directed radiation pressure, and where

$$\alpha = \frac{3E_\odot}{16\pi c^2 s\rho} = \frac{3.55 \times 10^{-8}}{s\rho} (\text{a.u.})^2/\text{year}.$$ 相対論参照

Robertsonガ見ツケタ運動方程式ノ動径方向トソレノ直角方向ノ成分ハ、

$$\ddot{r} - r\dot{\theta}^2 = -\frac{\mu}{r^2} - \frac{2\alpha\dot{r}}{r^2}, \qquad (1)$$

ト

$$\frac{1}{r}\frac{d}{dt}(r^2\dot{\theta}) = -\frac{\alpha\dot{\theta}}{r^2}. \qquad (2)$$

ココデ $\mu = GM - \alpha c$, ハ、外向キ方向ノ輻射圧ニヨル太陽重力定数ノ減少量デアツテ

$$\alpha = \frac{3E_\odot}{16\pi c^2 s\rho} = \frac{3.55\times10^{-8}}{s\rho}\ \mathrm{au^2/year},$$

デアル

(注)

We here denote by $E_\odot$ the total energy emitted by the sun per second, for which we have used the value 3.79×10^{33} erg/sec,[3] and by s and ρ the radius and density of the particle in question, expressed in c.g.s. units. It may be noticed at once that equation (2) integrates to

$$H = r^2\dot{\theta} = h - \alpha\theta, \qquad (3)$$

where H is the instantaneous value of the angular momentum and h is the initial value.

The secular perturbations for an osculating ellipse of semi-major axis a and eccentricity e have been calculated by Robertson and confirmed by us. For these two elements they are given by

$$\frac{da}{dt} = -\frac{\alpha(2+3e^2)}{a(1-e^2)^{3/2}}, \qquad (4)$$

$$\frac{de}{dt} = -\frac{5\alpha e}{2a^2(1-e^2)^{1/2}}. \qquad (5)$$

(③ コノ3ハ脚注ナリ)

E⊙ハ一秒間ニ放出サレル太陽ノ全エネルギデソノ値ハ 3.79×10^{33} erg/sec デ、s ト ρ ハ c.g.s. 単位デ表ワシタ微粒子ノ半径ト密度デアル。式(2)ハ直チニ積分サレテ次ノ様ニナルコトニ注目スベキデアロウ

$$H = r^2\dot{\theta} = h - \alpha\theta \qquad (3)\ *)$$

ココデ H ハアル瞬間ノ角運動量ノ値デ、h ハソノ初期値デアル

a ト e ノ永年摂動ハ Robertson ガ計算シ、我々ガ確カメタ。ソレラ2ツノ軌道要素ニツイテ次ノ様ニ表ワサレル

$$\frac{da}{dt} = -\frac{\alpha(2+3e^2)}{a(1-e^2)^{3/2}} \qquad (4)$$

$$\frac{de}{dt} = -\frac{5\alpha e}{2a^2(1-e^2)^{1/2}}. \qquad (5)$$

The only other secular change is the advance of perihelion, which is found by Robertson in the relativistic treatment to be

近日点ノ前進

$$\frac{d\pi}{dt} = \frac{3G^{1/2}M^{1/2}\mu}{c^2a^{5/2}(1-e^2)}. \qquad (6)$$

ホカノ永年変化ニツイテハ、近日点ノ前進ダケデアリ、ソレハ Robertsonノ相対論ノ取扱イニヨリテ次ノ様ニナッタ、

$$\frac{d\pi}{dt} = \frac{3G^{1/2}M^{1/2}\mu}{c^2a^{5/2}(1-e^2)}. \qquad (6)$$

---

*) $r^2\dot{\theta} = \mathrm{const.}$ ニツイテハ「天文計算入門」p.267 (35.3) ヲ参照ノコト

We now seek to find the long-term changes in these elements. It may first be noticed that the expression for perihelion advance is a maximum for large and dense bodies, where $\mu \cong GM$. For the cases in which we are interested, the rate of change is insignificant, amounting, for example, to 43″ per century for Mercury and less than this for small bodies of greater a and smaller e.

Of more interest are the changes in semi-major axis and eccentricity. If we deal with initially circular orbits, equation (4) is simplified and integrates to

$$t = \frac{a^2}{4\alpha} = 7.0 \times 10^6 s \rho a^2 \text{ years}, \tag{7}$$

where t is the total time of fall for a particle of radius s cm, density ρ gm/cm³, at an initial distance of a astronomical units. This formula is due to Robertson. For the more general case of eccentric orbits we can at least find a readily integrable relation between a and e from division of equation (4) by equation (5). The result, after integration, is

$$a = \frac{C e^{4/5}}{1 - e^2}. \tag{8}$$

水星の近日点 時の変化 を求めてみた 未了。

[a] Russell, Dugan, and Stewart, *Astronomy* (Boston: Ginn & Co., 1938), p. 534.

サテ コレラノ要素ノ永年変化ヲ見ツケルコトニシタイ。 近日点ノ前進ニツイテノ計算式ガ、大キクテ密度ノ高イ物体ニツイテ最大デアルコトガ最初ニ注目サレルベキダロウ。ココデ $\mu \cong GM$ デアル。我々ガ関心ヲ持ッテイル場合ニツイテ 僅カナ変化量ハ、例ヘバ 水星ノ100年ニツイテ 43″デアリ、微小天体ノ 大キナ a ト小サナ e ヲモツ小サイノデアル。

更ニ関心ノアルノハ 軌道半長径ト離心率ノ変化デアル。初メニ円軌道デアッタ場合ヲ取扱ウコトニスルト、式(4)ハ簡単ニナッテ 次ノ様ニ積分サレル。

$$t = \frac{a^3}{4\alpha} = 7.0 \times 10^6 s\rho a^2 \text{ 年}, \tag{7}$$

ココデ t ハ 半径ガ s cm デ密度ガ ρ gm/cm³ デアル粒子ガ落下スル全時間デ、最初ハ a 天文単位デアルトスル。コノ計算式ハ Robertson ニヨルモノデアル。離心率ガ大キイ、サラニ ツクトモ a ト e ノ関係ニツイテ容易ニ積分出来ル関係ヲ見ツケルコトガ出来ル。積分シタ結果ハ

$$a = \frac{C e^{4/5}}{1 - e^2}, \tag{8}$$

デアル。

(注) (8) ニツイテ。 (4)÷(5) ハ $\frac{da}{dt}\Big/\frac{de}{dt} = \frac{da}{de} = \frac{\alpha}{a}\frac{2+3e^2}{(1-e^2)^{3/2}} \cdot \frac{2a^2(1-e^2)^{1/2}}{5\alpha e} = \frac{2}{5}\cdot\frac{a}{e}\cdot\frac{2+3e^2}{1-e^2}$

$= \frac{2}{5}\frac{a}{e}\left(2 + \frac{5e^2}{1-e^2}\right) = \frac{4}{5}\frac{a}{e} + \frac{2ae}{1-e^2}$ $\quad \therefore \quad \frac{da}{a} = \frac{4}{5}\frac{de}{e} + \frac{2e}{1-e^2}de$ 両辺ヲ積分スルト、

$\log a = \frac{4}{5}\log e - \log(1-e^2) + \log C = \log\frac{C\cdot e^{\frac{4}{5}}}{1-e^2}$, 故ニ、$a = \frac{C\cdot e^{4/5}}{1-e^2}$. (8)

(5) ノ $\frac{de}{dt}$ ヲ (8) ノ a ニヨッテ書キカエルト、

$$\frac{de}{dt} = \frac{5\alpha e}{2a^2(1-e^2)^{1/2}} = \frac{-5\alpha e}{2\frac{C^2 e^{8/5}}{(1-e^2)^2}\cdot(1-e^2)^{1/2}} = \frac{-5\alpha(1-e^2)^{3/2}}{2C^2 e^{3/5}}.$$

ナオ、 $\alpha = \frac{3.55\times10^{-8}}{s\rho}$ au²/years デアルカラ

$\frac{2}{5\alpha} = \frac{2}{17.75}\times10^{8} s\rho = 0.113\times10^{8} s\rho = 1.13\times10^{7} s\rho.$

This relation is in contrast to the four-thirds power law found by Fessenkoff[4] for the nonrelativistic solution. The constant in equation (8) will hold at all times for any given particle, and, if we know a_0 and e_0 at any arbitrary time, it can be computed, once and for all, by solving for C:

$$C = a_0\, e_0^{-4/5}\,(1 - e_0^2)\,. \tag{9}$$

コノ関係ハ フェセンコフ[4] ガ 相対論ニヨラナイ解トシテ見ツケタ 4/3次法則ト対照的デアル.
式(8)ノ定数ハドンナ粒子ニモ常ニ成立ッテイル. 任意ナ時ノ a_0 ト e_0 ガワカット, Cニツイテ
解ケ関係ガイツデモ成立スル. ツマリ

$$C = a_0\, e_0^{-4/5}\,(1 - e_0^2). \qquad (9)$$

From the earlier equations it is not possible to find a relation $a = a(t)$ that is independent of e. However, by substituting equation (8) in equation (5), one finds a relation involving only the eccentricity and time,

$$\frac{d\,e}{dt} = -\frac{5\alpha\,(1 - e^2)^{3/2}}{2C^2\,e^{3/5}}.$$

Or

$$(t - t_0)_{\text{years}} = -\frac{2C^2}{5\alpha}\int_{e_0}^{e}\frac{e^{3/5}d\,e}{(1 - e^2)^{3/2}} = 1.13\times 10^7 s\,\rho\, C^2\int_{e}^{e_0}\frac{e^{3/5}d\,e}{(1 - e^2)^{3/2}}, \quad e_0 > e\,, \tag{10}$$

where s and ρ are in c.g.s. units. The constant C^2 has the dimensions (A.U.)^2 and is evaluated from equation (9) by using the constants of the orbit. Then $(t - t_0)$ is given directly

TABLE 1

THE TIME INTEGRALS

e	$G(e_0)$	$(t-t_0)/10^7\, s\rho q^2$ years	e	$G(e_0)$	$(t-t_0)/10^7\, s\rho q^2$ years
0.00	....	0.704	0.78	0.771	4.10
.05	0.0052	0.778	.80	0.846	4.42
.10	.0158	0.858	.81	0.889	4.60
.15	.0305	0.946	.82	0.934	4.79
.20	.0489	1.04	.83	0.983	5.00
.25	.0710	1.15	.84	1.04	5.23
.30	.0969	1.27	.85	1.10	5.49
.35	.127	1.40	.86	1.16	5.77
.40	.162	1.55	.87	1.23	6.08
.45	.202	1.72	.88	1.32	6.43
.50	.249	1.92	.89	1.41	6.83
.55	.305	2.15	.90	1.51	7.29
.60	.370	2.42	.91	1.63	7.82
.62	.400	2.54	.92	1.78	8.45
.64	.432	2.68	.93	1.96	9.22
.66	.468	2.82	.94	2.17	10.17
.68	.506	2.98	.95	2.45	11.39
.70	.548	3.16	.96	2.82	13.06
.72	.595	3.36	.97	3.37	15.50
.74	.647	3.57	.98	4.30	19.60
0.76	0.705	3.82	0.99	6.37	28.89

in years. Although the integral cannot be found directly, the integrand is independent of the particle under consideration, and numerical integrations can be performed that will hold for all cases. We have tabulated in the second and fifth columns of Table 1 the function

$$G(e_0) = \int_0^{e_0}\frac{e^{3/5}d\,e}{(1 - e^2)^{3/2}} \tag{11}$$

for interesting values of the eccentricity. Now, upon substitution of arbitrary particle radius, density, C^2, and the quantity tabulated in Table 1 for some initial eccentricity,

[4] *A. J. Soviet Union*, 23, 366, 1946.

p.137 we can find the total time for the particle in question to spiral into the sun. For the time between any two nonzero eccentricities, one, of course, uses the difference between the corresponding tabular values.

ハジメノ関係式カラ e ヲ含マナイ $a=a(t)$ ノ関係ヲ見ツケルコトハ不可能デアル。シカシ(8)ノ式ヲ(5)ニ代入スルコトニヨッテ離心率ト時間ダケヲ含ム関係ヲ見ツケルコトガ出来ル。

(注)(式ハ(5)ノ終リニ示サレテイル。コノ式ヲ dt ニツイテ積分スルト)

$$dt = -\frac{2C^2}{5\alpha}\frac{e^{3/5}}{(1-e^2)^{3/2}}de \text{ デアルカラ}$$

$$(t-t_0)_{years} = -\frac{2C^2}{5\alpha}\int_{e_0}^{e}\frac{e^{3/5}\,de}{(1-e^2)^{3/2}} = 1.13\times10^7 s\rho\, C^2\int_{e}^{e_0}\frac{e^{3/5}\cdot de}{(1-e^2)^{3/2}}, \quad e_0 > e, \qquad (10)$$

(注) $\int_a^b f\cdot dx = -\int_b^a f\,dx$

ココデ s ト ρ ハ c.g.s 単位デ表ワサレテイル。定数 C^2 ハ $(AU)^2$ ノ次元ヲ持ッテイテ、軌道ノ定数ヲ用イテ(9)ニヨッテ求メラレル。ソシテ $(t-t_0)$ ハ年デ表ワサレル。

積分ハ簡単ニハ求メラレナイガ、被積分式ハ、今考ヘテイル粒子ニハ無関係デ、全テノ場合ニ成リ立ツ積分ノ数値ヲ求メルコトガ出来ル。Table 1 ノ 2番目ト5番目ノ欄ニ、e ニツイテノ

$$G(e_0) = \int_0^{e_0}\frac{e^{3/5}\,de}{(1-e^2)^{3/2}} \qquad (11)$$

ノ値ガ示シテアル。粒子ノ半径、密度ト C^2 ト、初期値ニツイテ Table 1 ニ示サレテイル値ヲ用イテ太陽ニ、ラセン形ノ軌道ヲ描イテ落下スルニ要スル全体ノ時間ヲ知ルコトガ出来ル。ゼロデナイ離心率ノ、2ツノ値ノ間ニ要スル時間モ、モチロン対応スル表値ノ差ヲ用イテ知ルコトガデキル。

p.137, 4行目 For total times of fall to the sun from any initial eccentricity in terms of particle radius, density, and perihelion distance, the calculation can be made far simpler, although less general, by a reduction of equation (10). From equation (8), since

$$q = a(1-e),$$

we find

$$C^2 = q^2(1+e)^2 e^{-8/5}. \qquad (12)$$

And thus, for total time of fall to the sun,

$$(t-t_0)_{\text{years}} = 10^7 s\rho q^2\left[\frac{1.13\,(1+e_0)^2}{e_0^{8/5}}\int_0^{e_0}\frac{e^{3/5}de}{(1-e^2)^{3/2}}\right]. \qquad (13)$$

13式が求大切

We give in Table 1, third and sixth columns, the bracketed quantity in equation (13). For numerical results it is now required only to substitute for s and ρ in c.g.s. units and q in astronomical units. The latter quantity is directly available in most cometary and meteoric catalogues. It should be noted, however, that these results hold only for total time of spiraling into the sun and that the second and fifth columns of Table 1 should be used for the times between two arbitrary eccentricities.

最初ノ離心率ノ値カラ、太陽ニ落下スルマデノ全時間ニツイテ、粒子ノ半径、密度ト近日点距離ニヨッテ、アマリ一般的デハナイガ、式(10)ヲ改変シテ計算ヲ簡単ニスルコトガ出来ル。式(8)カラ、$q=a(1-e)$ デアルカラ

$$C^2 = q^2(1+e)^2 e^{-8/5} \qquad (12)$$

トナル

(注) $q=a(1-e)$ カラ $a=q(1-e)^{-1}$、$1-e^2=(1+e)(1-e)$ デアルカラ $(1-e^2)^2=(1+e)^2(1-e)^2$ ヨッテ(9)カラ、$C^2=a^2e^{-8/5}(1-e^2)^2 = q^2(1-e)^{-2}\cdot e^{-8/5}\cdot(1+e)^2(1-e)^2 = q^2(1+e)^2 e^{-8/5}$ (12)

(12)ノ C^2 ヲ(10)ニ代入スルト

$$(t-t_0)_{years} = 10^7 s\rho q^2\left[\frac{1.13(1+e)^2}{e^{8/5}}\int_0^{e_0}\frac{e^{3/5}\cdot de}{(1-e^2)^{3/2}}\right]. \qquad (13)$$

トナル

Table 1 ノ3番目ト6番目ノ欄ニ式(13)ノカッコ[ ]ノ中ノ値ヲ示ス。数値計算ノ結果ハ、S ト ρ ヲ c.g.s 単位デ、q ヲ天文単位デ代入スルコトダケガ要求サレテイル。ソノ後ノ数値ハ、多クノ彗星ヤ流星ノカタログカラ直接ニ与ヘラレル。シカシコレラノ結果ハ太陽ニラセン状ニ落下スル時間ダケデアッテ、Table 1 ノ第2ト第5欄ハ、2ツノ任意ノ離心率ノ差ニツイテ用イラレルベキデアルコトヲ注意シタイ。

Using the general relations for $a = a(e)$ and $q = q(e)$ in equations (8) and (12) in combination with that for $e = e(t)$, it is a straightforward matter graphically to relate semi-major axis or perihelion distance directly to the time. A calculation of $a(t)$ for various known meteor orbits shows a reasonably linear decrease of semi-major axis with the time to a given point, which depends on the value of C for the orbit in question, but averages about 1 A.U. Then the decrease in a is accelerated, and finally the particle falls into the sun in very short order. A plot of $q(t)$ shows a very slow decrease over most of the time but finally, also, a fast drop into the sun. The curves in Figure 1 show the nature of these relations for the Giacobinid and Leonid meteor showers.

The application of these results to small particles is interesting. As has been pointed out, the operation of the Poynting-Robertson drag should have been effective in sweeping out rather large volumes of the solar system in astronomically short times. For example, in the slowest case, that of bodies in circular orbits, we find that all particles of density 4 gm/cm³, radius $\leq$ 1 cm. and initially within a sphere of radius of 1 A.U. centered on the sun, will fall into the sun in a period of 2.8×10^7 years.

式(8)ト(12)ノ一般的ナ関係 $a=a(e)$ ト $q=q(e)$ ヲ用イテ $e=e(t)$ ト合セテ、軌道半長径ト近日点距離ノ時間トノ関係ガグラフデ直接的ニ見ルコトガ出来ル。既知ノ流星軌道ノ $a(t)$ ノ計算結果ハ、軌道半長径ガ時間ト共ニ直線的ニ減少シテイルコトガワカル(Fig.1)。ソレハコノ軌道ノ C ノ値ニ依存シテイテ、平均約1天文単位デアル。ソシテ a ノ減少ハ加速度化サレテイテ、最終的ニ粒子ハ太陽ニ大ヘン短時間ニ落下スル。$q(t)$ ノ表示ニヨルト、殆ド全時間ニワタッテ大ヘンユックリ減少シテイテ、最後ニハ、コレモマタ速ク太陽ニ落下スル。第1図ハ、ジャコビニ群トしし座群ノコレラノ関係ノ性格ヲ示シテイル。

小サイ微粒子ニコレラノ結果ヲ適用スルコトハ興味アルコトデアル。既ニ指摘シタ様ニ P.R. ノ抵抗作用ハ、太陽系内ノ比較的大キイ物体ヲ、天文的ニハ短時間デ掃出スコトニ効果的デアッタ。例エバ、最モ遅イ場合デ、円軌道ニアッタ物体デ密度ガ 4gm/cm³ デ半径≦1cm、最初太陽ヲ中心トスル半径1天文単位ノ球形ノ中ニアッタモノハ、太陽ニ 2.8×10^7 (2800万)年ノ時間デ落下スルノデアル。

($e=0.00$ デ $s=4$, $\rho=1$, $q=1$ トスルト $0.704\times4\times10^7 = 2.8\times10^7$ 年)

We have selected several of the known meteor showers, and, using Yamamoto's[5] elements for the parent-comets (except for the parentless Geminid shower, where we have used Whipple's[6] elements for a photographed meteor), we have calculated the total time for these shower particles to fall into the sun. The results are shown in Table 2. The first four columns are self-explanatory; the fifth gives the constant C appearing in equation (8); the sixth gives the times of fall as computed from Table 1 in terms of particle radius and density; and the seventh gives, by way of comparison, the times as calculated from equation (7), assuming circular orbits. For example, a particle of radius 0.05 cm, corresponding to about a fifth-magnitude meteor, and of density 4 gm/cm³ moving in the orbit of Halley's Comet would be drawn into the sun in about ten million years. It can be seen from the sixth column of Table 2 that the lifetimes of faint visual meteoric bodies in the well-known showers are relatively short astronomically.

イクツカノ既知ノ流星群ヲ選ビ、山本博士ノ彗星カタログノ母彗星(母彗星ガナイ双子座群ハ、ホイップルノ写真流星ノ軌道要素ヲ用イタ以外ハ)ノ軌道要素ヲ用イテ、コレラノ流星群ノ粒子ガ太陽ニ落チルマデノ時間ヲ計算シタ。結果ハ Table 2 ニ示サレテイル。始メノ4欄ハ自分デ理解スルコトガデキルダロウ。第5欄ハ式(8)ニアル定数Cデ、6番目ハ粒子ノ半径ト密度ニヨッテ第1表デ計算デキル落下時間ヲ示ス。7番目ハ円軌道ト仮定シテ式(7)ニヨッテ計算デキル落下時間ヲ比較ノタメニ示ス。例エバ半径0.05cmデ、ソレニ対応スル光度ハ約5等デ、密度ハ 4gm/cm³、ハレー彗星ノ軌道ヲ動イテイルモノハ約1000万年デ太陽ニ落下スル。Table 2 ノ第6番目ノ欄カラハ、ヨク知ラレタ流星群ノ肉眼流星ノ寿命ガ天文的ニハ比較的短イコトガワカル。

暗イ(5等級)

We inquire now as to the possibility of observing the Poynting-Robertson effect during a meteor shower. From equation (10) it is evident that the times involved depend → p.139 (9)

[5] *Pub. Kwasan Obs.*, Vol. 1, No. 4, 1936.

[6] *Proc. Amer. Phil. Soc.*, Vol. 91, No. 2, 1947.

流星群ノ期間中ニ P.R.効果ヲ観測スルコトガ出来ル可能性ニツイテ尋ネタイ。式(10)カラ
含マレテイル時間ハ粒子ノ大キサト密度ニ直線的ニ(一次式ノ関係デ)関係シテイルコトガ明ラカデアル。
(p.139, (9)ノ判読困難ノ訳)

p.138

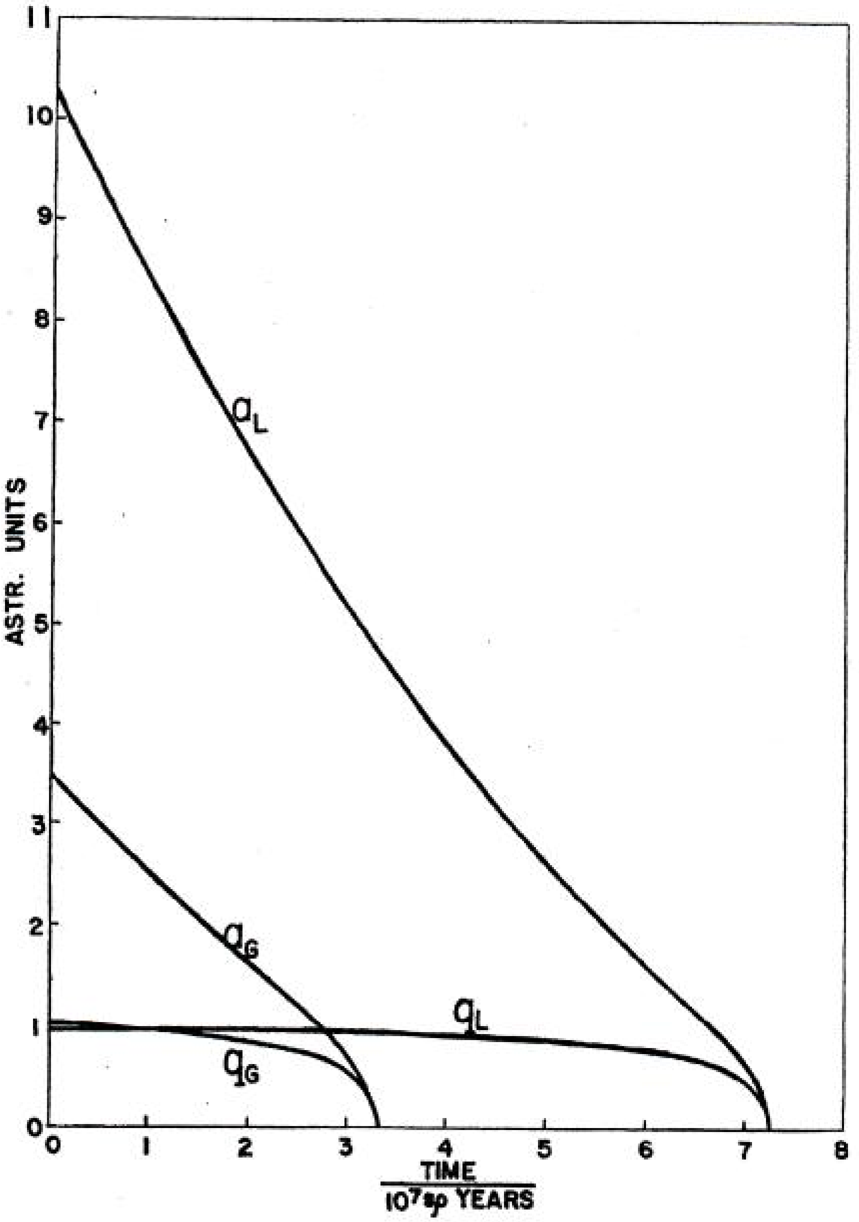

FIG. 1.—Semi-major axis and perihelion distance as functions of the time for two showers. Subscripts L refer to the Leonids and G to the Giacobinids. Times are reckoned from the present epoch.

第1図 2ツノ流星群ニツイテ時間ノ関数トシテノ半長径軸ト近日点距離。添字ノ L ハしし座群
G ハジャコビニ群ヲ示ス 時間(Time)ハ現在カラ測ッタモノデアル。
(Table 2ニヨルト $(t-t_0)/10^7 s\rho$ ハ L: 7.24 Giacobinids: 3.32, a ハ L: 10.325, G: 3.520)

P.139 linearly on the particle size and density. Let us make the simplifying assumptions, first, that the density of every meteoric particle is 4 gm/cm³ and, second, that a meteor shower originates as a uniformly dense swarm occupying an elliptical orbit with small circular cross-section in the plane normal to the velocity vector of the particles. If there is dispersion in the individual meteor radii, the smaller ones will be drawn toward the sun far faster than will their larger neighbors. At some time later, the cross-section of the swarm will be elongated in the radial direction relative to the sun, with the smaller particles orbiting closer to the sun. The conditions for observing this effect on earth are that the inclination of the shower shall be moderately low or retrograde and that enough time shall have elapsed since the formation of the shower for the various-sized particles to have been separated sufficiently for detection.

仮定ヲ簡単ニシテオコウ。初メニ流星体ノ密度ヲ4gm/cm³ 2番目ニ，流星群ハ，粒子ノ運動速度ニ対シテ直角ノ平面内ニ小サイ円形ノ断面ヲ持チ，楕円軌道上ニ一様ニアッテ密度ノ濃イ流星群ヲ成シテイルモノトスル。モシ個々ノ流星半径ノ値ガ分散シテイルトスレバ小サイモノハ，ソノ近クニアル大キイモノヨリ早ク太陽ニ引ッパラレル。ソシテ後ニハ流星群ノ断面ハ太陽ニ関シテ動径ノ方向ニ伸ビルダロウ，小サイ粒子ハ(大キイモノヨリ)太陽ノ近クヲ運動スルコトニナル。地球カラコノ効果ヲ観測スル条件ハ，流星群ノ軌道傾斜角ハ，ヤヤ低クナルカ マタハ逆行スル様ニナリ，イロイロナ大キサノ粒子ガ，判断出来ルグライ充分ニ分離スル様ニナルニハ，流星群ガ生成シテカラ充分ナ時間ガ経過シナケレバナラナイ。

As an approximation to the orders of time involved in separating bright and faint particles for observation, we take all the above-listed showers with $i < 40°$ and assume

TABLE 2

TIMES OF FALL FOR SHOWER PARTICLES (流星群ガ太陽ニ落下スルマデノ時間)

Shower	Parent-Comet	a	e	C	$(t-t_0)/10^7\, sp$ years	$(t-t_0)_{\min}/10^7\, sp$ years
Geminids........	....	1.396	0.900	0.289	0.143	1.4
Taurids......	Encke	2.210	.8498	0.6995	0.605	3.4
Bielids.......	1852 III	3.5259	.75592	1.8902	2.79	8.7
Giacobinids...	1933 III	3.520	.7160	2.241	3.32	8.7
Orionids?.....	Halley	17.96	.9673	1.186	5.10	230
Leonids.......	1866 I	10.325	.90542	2.0145	7.24	75
Perseids......	1862 III	24.277	.96035	1.9491	12.2	410
Lyrids........	1861 I	55.665	0.98346	1.8508	18.6	2200

TABLE 3

TIMES OF SEPARATION (分離スル時間)

Shower	Years	Shower	Years
Geminids..........	7×10^4	Bielids...........	2×10^6
Taurids...........	5×10^5	Leonids..........	3×10^6
Giacobinids........	1×10^6	Orionids?.........	5×10^6

that all $i = 0°$, that the earth's orbit is circular, and that the perihelion advance of the shower is of no consequence. We now inquire how long it will take to separate fifth-magnitude meteors from those of magnitude −2, so that the earth will pass from one limit to the other in a period of 5 days.*) It should then be possible to observe a gradually changing mean magnitude over the period. The radii of such meteors are calculated separately for each shower. We take, as before, a density of 4 gm/cm³. We then apply to Watson's[7] values of mass, which were computed for meteors with velocity of 55 km/sec, a correction for the actual observed shower velocities listed by him.[8] *)→(10)

明ルイノト暗イ粒子ノ分離ガ観測デキル様ニナルタメノ時間ノ大キサヲ近似的ニ求メルタメニ上記ノ$i<40°$ノ全テノ流星群ノ全テヲ$i=0°$ト仮定シテ，地球軌道ハ円$(e=0)$トシ，近日点ノ前進ハ考ヘニ入レナイコトトシタ。光度−2ト5等ノ流星ガ分離シ，従ッテ地球ガコレラノ限界ヲ5日間デ通リ抜ケル様ニナル時間ヲ求メタイ。→(10)

㊟ This correction factor is calculated on the assumption that the kinetic energy of a meteor is proportional to its luminosity. The steps in the geometrical approximation applied are to solve for the present true anomaly of the intersection of earth and shower, to increase this by 5°, to find by equation (8) the new a and e satisfying the new true anomaly, and to integrate between the old and new eccentricities to determine the time. The results indicate the correct order of magnitude for the times of separation and are given in Table 3. Definitive correlations → p.140

[7] *Between the Planets* (Philadelphia: Blakiston Co., 1941), p. 115.

[8] *Ibid.*, p. 123.

→ (9) ノ下カラ5行目カラ.

コノ期間中ニ流星ノ平均光度ガユックリ変ワレバ、コレヲ観測スル可能性ガアルニ違イナイ。コノ様ナ流星ノ半径ハ、ソレゾレノ流星群ゴトニ計算スル。先ト同様ニ密度ヲ $4 gm/cm^3$ トスル。質量ハワトソンWatsonノ値ヲ採用スル。ソレラハ流星速度ヲ55km/secトシテ計算サレ、実際ノ速度補正ハ後ニヨッテリストサレテイル（ウト8ノ注ヲ参照ノコト）.

㊟ コノ補正係数ハ流星ノ力学的エネルギーハ明ルサニ比例スルトノ仮定ニヨッテ計算サレテイル。適用サレタ幾何学的近似ノ過程ハ、地球ト流星群ガ交差スル点ノ真近点離角ヲ求ドンダメニ式(8)ニヨッテ新シイ真近点角ヲ満足スル a ト e ヲ求メルタメニ5°ヅツ増加スル方法デアル。ソシテ時間ヲ求メルタメニ新旧ノ離心率ノ間隔ニツイテ積分スルコトデアル。コノ結果ハ分離時間ノ正シイ大キサヲ示シテイテ、Table 3ニ示サレテイル。

of magnitude and time apparently are not found in observations of meteor showers. A shower may be of very recent origin so that the particles have not had time to become separated radially. Such may be the case with the Giacobinids. Among the older showers, where the magnitude effect should appear, those with orbits of low inclination and therefore favorable for observation of the effect are also most seriously affected by planetary perturbations. Since these perturbations are nonselective with respect to particle size but may be capable of dispersing the showers, the times given in Table 3 must be considered only as upper limits to the possible ages of the showers. It may be possible in the near future, by combining extensive data from visual, photographic, and electronic observations of meteor showers, to detect a systematic effect of the sort that we have outlined above.

光度ト時間トノ確カナ相関々係ハ流星群ノ観測デハハッキリトハ見ツカラナイ。流星群ハ恐ラク最近生成シタモノデアロウ。従ッテ流星ガ動径方向*ニ分離スル程ニナル時間ヲ持ッテイナイダロウ。*放射状ニトスベキカ？ コレハジャコビニ群ノ場合ガソノ様デアル。古イ群ノ中デハ、光度効果ガ表ワレテイル筈ノ群デハ傾斜角ガ低ク、コノ効果ヲ観測スルニハ有利デアルガ、ソレラハ惑星摂動ニヨッテ大キク影響サレテイル。コレラノ摂動ハ流星体ノ大キサニハ無関係デ流星群ヲ分散サセルコトガ出来ルノデ、Table 3ニ与ヘラレテイル時間ハ流星群ノ可能ナ寿命ノ上限トシテ考ヘルベキデアル。上ニ概要ヲ述ベタ系統的ナ効果ノイロイロヲ、眼視ヤ、写真、電波観測ナド多クノデータヲ組合セテ検出スルコトガ近イ将来可能ニナルダロウ.

Although meteor showers have in nearly all cases been identified with comets, the origin of sporadic meteors is not so clear. It is possible that some sporadic meteors have a common origin with the meteorites, which Harrison Brown and Claire Patterson[9] have shown to be planetary debris. It seems justified to make the unproved assumption that meteorites and asteroids are associated generically. Since the mean semi-major axis for the known asteroids is about 3 A.U., we may assume, in addition, that the parent-planet (or planets) of the meteorites disintegrated at about this distance from the sun. Particles

流星群ハ、殆ド全部彗星トノ関係ガワカッテイルケレドモ、散在流星ノ起源ハハッキリシテイナイ。イクツカノ散在流星ハ隕石ト同ジ起源ヲ持ッテイル可能性ガアルガ、ハリソン・ブラウントクレイグパターソン[9]ガ惑星ノ破片デアルコトヲ示シテタ。一般ニ隕石ト小惑星ハ互イニ関連シタモノデアレトデアロウ未確定ノ推定カ正シイトサレタ様デアル。既知ノ小惑星ノ軌道半長径ノ平均ガ約3天文単位デアルカラ、コレニ加ヘテ、隕石ト母惑星(マタハ母惑星タチ)ハ太陽カラ約コノ距離デ分裂シタト考ヘテヨイダロウ。(10)頁下ヘ

TABLE 4

TIMES OF FALL FOR ASTEROIDAL PARTICLES (小惑星的微粒子ノ落下時間)

q	q'	a	e	C	t
5	5	5	0.00	....	$70\times10^7\,s$
3	3	3	.00	....	25 〃
3	5	4	.25	11.4	11 〃
1	3	2	.50	2.60	1.9 〃
1	5	3	0.67	2.31	$2.9\times10^7\,s$

thrown past the orbit of Jupiter, if not lost immediately to the solar system, would generally move in orbits with an apse near Jupiter's orbit. Hence most potential meteors from such a disrupted planet would have orbits lying entirely within that of Jupiter. The total times of fall to the sun for particles of density 4 gm/cm^3 in a few such orbits are given in Table 4. The column headings are, successively, perihelion distance, aphelion distance, semi-major axis (all in astronomical units), eccentricity, C as calculated from equation (9), and the time in years in terms of particle radius.

昔、木星軌道ニナゲコマレタ微小天体ハ、直チニ太陽系カラ失ワレタノデハナイナラバ、木星軌道ノ一番奥(apse、遠日点)ノ近クヲ運動シテイル筈デアロウ。従ッテ、コノ様ナ破壊サレタ惑星カラ出来タ流星体ノモトニナルモノノ多クハ、木星軌道ノ内側ニ横タワッテイル軌道ヲ持ツコトニナルダロウ。密度ガ4gm/cm^{3}ノ微粒子デコノ様ナ軌道ニアル粒子ガ太陽ニ落下スルマデノ時間ガTable 4ニ与ヘラレテイル。表ノ欄ハ順ニ、近日点距離、遠日点距離、軌道半長径(全テ天文単位デ表ワサレテイル)、離心率、式(9)デ計算サレタCト、粒子半径ニヨル年数、デアル。

Let us consider, first, what sorts of particle will have been eliminated within the duration of the short cosmic time scale. The slowest bodies are those in a circular orbit at 5 A.U., and from Table 4 it is clear that all bodies of radius less than about 4 cm must have been swept into the sun within this time. Thus, for an assumed explosion 3×10^9 years ago, all meteoric bodies arriving on the earth from the asteroid belt must be very bright. However, if we assume a planetary breakup sixty million years ago, as suggested by Bauer,[10] it appears that all particles originating with the asteroids and of radius less than 0.08 cm must have been lost into the sun. It is probable, therefore, that the supply of sporadic material giving meteors fainter than about the fifth magnitude must be cometary or interstellar in origin, except possibly for a few stragglers from asteroidal collisions.

In considering the Poynting-Robertson effect in regions external to the solar system, the time for a body in a given orbit will be equal to that for the same body in the same orbit around the sun multiplied by the factor $E_{\odot}/E$, the ratio of the total energy per sec-

[9] *J. Geol.*, **56**, 85, 1948.

[10] *Phys. Rev.*, **74**, 501, 1948.

短イ宇宙時間ノ期間以内ニ消失シテシマウイカ種類カノ粒子ニツイテ、先ニ考ヘテミヨウ。最モ遅イモノハ5天文単位ノトコロノ円軌道ヲ持ッテイル様ナモノデ、Table 4ニヨルト、半径約4cm以下ノモノハ、コノ時間(約3億年)以内ニハ掃出サレテシマウコトガ明ラカデアル。従ッテ30億年前ノ爆発ヲ仮定スルト、小惑星帯カラ地球ニ到着シタ全テノ流星体ハ大変明ルイニ違イナイ。シカシ、惑星ノ破壊ガ、バウエル[10]ガ云ウ様ニ6000万年前デアルト仮定スルト、小惑星ト一緒ニ生成シ半径ガ0.08cm以下デアル微粒子ハ全テ太陽ニ落下シテナクナッタト考ヘラレル。従ッテ5等級ヨリ暗イ流星ヲ与ヘル散在物質ノ供給ハ、恐ラク小惑星トノ衝突ニヨッテ分離サレタモノヲ除キ彗星起源カマタハ恒星空間起源デアロウ。

p.140, 下カラ3行目, 太陽系ノ外ノ区域デ、P.R.効果ヲ考ヘル場合ニハ、与ヘラレタ軌道ヲ持ツ天体ノ時間
ヲ考ヘルニハ、太陽ノ周リノ軌道ト同ジ軌道ヲ持ツ同ジ大キサノ物体ニ、太陽カラ放射サレル1秒間アタリノ全エネル
ギト母天体ニヨッテ放射サセルエネルギートノ比、$E_{\odot}/E$ヲ係数トシテ乗ズレバ同ジコトニナル

p.141

ond emitted by the sun to that emitted by the parent-star. In order to utilize the results given above, we must, of course, continue to express a and q in astronomical units. Near the large and hot B stars the times will be shorter than those near the sun by a factor of about 100,000, whereas for particles near M dwarfs the times will run approximately one hundred times as long.

上ニ与ヘラレタ結果ヲ用イルタメニハ、モチロン、aトqヲ天文単位デ表ワシテ、用イ続ケナケレバナラ
ナイ。大キクテ熱イB型星ノ近クデハ、落下時間ハ、約100,000ノ割合デ太陽ノ近クノ場合
ヨリモ短カクナル。M型星ノ近クノ粒子ニツイテハ、サラニ100倍グライ、近似的ニ長クナル。

The nucleus of the galaxy gives a negligibly small effect on the orbits of interstellar particles. What effect there is depends markedly on the co-ordinates of the particle concerned, since the net radiative flux vector due to the Milky Way will vary in magnitude and direction at each point of space because of the irregular distribution of bright clusters and overlying dark clouds. However, even for an idealized unobscured galaxy of absolute magnitude -15 and radius 1000 parsecs, where $E_{\odot}/E$ may be taken as about 10^{-8}, it is found that the time to spiral into the nucleus for a body of $s\rho \leqq 4$ is 10^{16} years for an initially circular orbit. And, although for highly eccentric orbits the times may be less by a factor of, say, 100, it is clear that the Poynting-Robertson effect has been of very little significance galactically. Its importance is restricted to small particles orbiting in the vicinity of individual stars.

銀河ノ中心核ハ、星間空間ニ(粒子ノ)アル軌道ニ対シテハ無視出来ルクライノ小サイ効果シカ与ヘナイ。
粒子ノ座標ニヨッテドノ様ナ効果ガアルダロウカ。銀河系ニヨル放射量ノベクトルハ、ソノ
量ヤ方向ガ、明ルイ星団ヤ横タワッテイル暗黒星雲ノ異常ナ分布ニヨッテ大キク変化
シテイルカラデアル。シカシ、絶対光度ガ−15等、半径ガ1000パーセックノ理想的ナ観測デキ
ナイ銀河ニツイテデモ、$E_{\odot}/E$ハ約10^{-8}トシテ、始メ円軌道デ、$s\rho \leqq 4$ノ物体ガ、中心核ニ
落下スルマデノラセン軌道ヲ描ク時間ハ10^{16}年デアルコトガワカル。ソシテ離心率ガ大キイ軌道
デモ、落下時間ハ小サク、例エバ1/100デ、P.R.効果ハ、銀河宇宙デハ大ヘン小サイコトハ明ラ
カデアル。コノ効果ノ重要性ハ、個々ノ恒星ノ近クデ回ッテイル、小サイ粒子ニ限ラレテイ
ルノデアル。

Ap. J 111, 134–141, (1950)

Luigi G. Jacchia ルイジ・ジ・ヤキア
in The Solar System III, Meteors, Meteorites, and Comets
pp. 783—785.

p.783 3.3. The Yarkovski – Radzievsky Effect
ヤルコブスキ－ラディエブスキ効果

ポインティング－ロバートソン効果ハ，重力デ動イテイル粒子ニヨッテ吸収サレタ太陽エネルギーガ動径方向ニ一様ニ再放射サレルト仮定シテイル。シカシ粒子ガ回転シテイルト，吸収方向ト放射方向ニ差ガ出来テ，コノ差ハ粒子ノ自転角ノ速度ニ左右サレル。マタ粒子ノ大キサヤ熱伝導率ニモ関係スル。コノ差ノ結果，横方向ノ力ガ生ジ，コレガP.R効果ト同ジ様ニ働キ，自転ト軌道運動ガ反対方向デアレバ，コノ力ハ減衰（P.R.効果）ニ加算スル様ニ働キ，モシ自転ト軌道運動ガ同方向デアレバ差トナッテ働ク。コノ効果ハ，エピック（1951，マタLovell 1954 p.410ヲ見ヨ）ニヨレバ，1900年ゴロYarkovskiニヨッテ指摘サレタ。1952年ニラディエブスキガ，ヤルコブスキトエピックノ論文ヲ知ラナイデ独立ニ同ジ効果ニツイテ，エピックト本質的ニ同ジ結論ニナルコトヲ発表シタ。

結論ハ次ノ通リデアル。コノ効果ハ粒子ノ回転周期ノ平方根ニ比例スルノデ，
p.784 小惑星ヤ隕石ニハ重要ニナリ，普通ノ隕石ト同ジ大キサノ粒子デハ無視デキルニチガイナイ。隕石ハカナリ早ク自転シテイルト推定サレル。シカシコノ最後ノ問題ハマダ決ッテハイナイ。エピックノ結論ハ，小惑星ノ小サイ破片ハソノ大キサニ比例スル自転周期ヲ持ツトイウノデアリ，コレハ短周期（？若イ）彗星破片ニハ適用サレナイ仮定理論ニ基ヅイテイルノデアル。ラディエブスキ（1954）ハ，続キノ論文デ，太陽系ノ小物体ノ自転ハ輻射圧ニヨッテ加速サレルコトヲ知ッタ。彼ノ議論ハ次ノ通リデアル。[illegible]ニ反射シテイル物体ハ，ソノ輻射圧ノ結果トシテノベクトル（C 放射方向）ハ，慣性力ノ中心ヲ通ラナイ。ソシテコレハトルク（ネジリ力）回転力ヲ生ジルコトニナロウ。彼ハコノ効果ガ小惑星ヤ隕石ヲ破壊スルコトニ効果的ニ作用スルノデ大ヘン重要ナコトダト考ヘタ。シカシ，[illegible]ナ磁場ガ惑星間空間ニ存在シテレバ，鉄磁性ノアル小サナ粒子ノ回転ヲ簡単ニ遅クスルトイウコトヲ指摘シテオカネバナラナイ。普通ノ流星微粒子ノ回転周期ハ0.1〜1秒ノ程度デ，コレガヤルコブスキ－ラディエブスキ効果ヲ予想ヨリモズット重要ナモノニシテイルコトヲ考ヘナケレバナラナイ。

（注）

3.4 Corpuscular，粒体。太陽カラ来ル微粒子ノ影響ヤ
3.5 他ノ抵抗物質ノ影響ヲ考ヘナケレバナラナイ
トイウガ，詳シイコトハワカラナイヨウデアル。