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ABSTRACT

Using the University of Iowa's Pioneer 10 electron model, we have calculated the synchrotron radiation at 375 cm expected at Earth from the region $L=2.9-5\ R_J$ of Jupiter's magnetosphere. The result is ∿21 flux units (f.u.). This value is to be compared with 6.0 ± 0.7 f.u., the flux density of synchrotron radiation measured from Jupiter's entire magnetosphere in ground based radio observations. We find that most of the radiation at 375 cm is emitted by electrons in the 1-10 MeV range. If the Iowa model is cut off below 10 MeV, our calculated flux is reduced to ∿4 f.u., a level compatible with the radio observations.

In the year since Pioneer 10's encounter with Jupiter there has been considerable discussion and concern that the energetic electron experiments aboard are yielding results incompatible with ground based observations of synchrotron radiation, which presumably is produced by these same electrons. Northrop and Birmingham (1974) previously showed that their Pioneer 10 - based calculations of the synchrotron emission at 10.4 cm are reasonably consistent with interferometric measurements at that wavelength. The concern, however, is that Pioneer 10 level fluxes produce increasingly too much synchrotron radiation at longer wavelengths, Luthey et al, 1975.

Again using the spectrum derived from the University of Iowa electron measurements, we have calculated the incoherent synchrotron emission at 375 cm, the longest wavelength at which Jovian synchrotron radiation has been observed by radio astronomers. For this calculation, we adopt the geometry shown in Fig. 1. Jupiter's magnetic field $\underset{\sim}{B}$ is taken to be that of a centered dipole oriented perpendicular to Earth's line of sight. The strength of the field is 4 Gauss at the surface of Jupiter at the magnetic equator. Convenient spatial coordinates are dipole L, latitude λ, and azimuth ϕ.

The radio measurements at 375 cm are flux values for Jupiter's entire magnetosphere. For comparison purposes we therefore evaluate the emission in the x-direction from each infinitesimal volume element of the Jovian magnetosphere and then integrate over ϕ, λ and finally L. (A ϕ-dependence to the emission enters because at fixed λ, Earth's look angle θ with respect to the magnetic field depends on ϕ).

The radiation P_1 (in mks units) emitted per steradian, per Δf (Hertz) centered at frequency $f(=\frac{\omega}{2\pi})$, in the direction θ by <u>one</u> electron of speed

$v = \beta c$ and local pitch angle δ, is the sum of two terms

$$P_1 = \frac{e^2\omega^2}{4\pi\varepsilon_0 c\omega_0}\left[\beta^2 \sin^2\delta\, J_\nu'^{\,2}\left(\frac{\omega}{\omega_0}\,\beta\sin\theta\sin\delta\right) + \left(\frac{\cos\theta-\beta\cos\delta}{\sin\theta}\right)^2 J_\nu^{\,2}\left(\frac{\omega}{\omega_0}\,\beta\sin\theta\sin\delta\right)\right] \qquad (1)$$

$\omega_0(v,L,\lambda)$ is the relativistic gyrofrequency and J_ν the ordinary Bessel function of order $\nu = \omega(1-\beta\cos\delta\cos\theta)/\omega_0 >> 1$. The first term represents radiation polarized $\perp$ to the local $\underset{\sim}{B}$ and the second radiation polarized $||$ to $\underset{\sim}{B}$. Each term contributes to <u>both</u> orthogonal polarizations received at Earth in an amount which depends on L, λ, and ϕ. For the region of Jupiter's magnetosphere that we have considered, the perpendicular polarization is about a factor of 10 larger than the parallel; we shall henceforth consider only the term in (1) proportional to $(J_\nu')^2$.

To determine the total emission in the x direction from the magnetospheric point L, λ, ϕ, we integrate (1) over the density of electrons $n(T,\delta,L,\lambda) = j(T,\delta,L,\lambda)/v$

$$P_2(L,\lambda,\phi) = \int_0^\infty dT \int_0^\pi d\delta\; j(T,\delta,L,\lambda)\; P_1\,(T,\delta,L,\lambda,\phi)/v \qquad (2)$$

(T is electron kinetic energy). For the electron flux j, differential in T and solid angle, we again use the Iowa empirical model

$$j(T,\delta,L,\lambda) = \frac{k(L)\Gamma(L)}{2\pi S(n)}\; T^{-(\Gamma+1)}\; \frac{\cos^{3n(L)}\lambda}{(1+3\sin^2\lambda)^{n/4}}\;\sin^n\delta \quad (T \text{ in MeV}) \qquad (3)$$

This formula has been developed from the Pioneer 10 electron measurements of the Iowa group (Van Allen et al, 1974). It is based primarily on integral flux measurements above thresholds of 21 MeV and 31 MeV; its use at energies far below 21 MeV is an extrapolation. The parameters of the model are discussed in Northrop and Birmingham (1974) and are listed in Table 1 for the region between periapsis at $L=2.9\ R_J$ and an outer limit of $L=4.9\ R_J$ at which synchrotron radiation has become very small. We have made no attempt as yet to extrapolate to the region $L<2.9\ R_J$.

The energy integral in (2) is effectively cut off at a lower limit T_{min} by the ineffective radiative capacity of low energy electrons and at an upper limit T_{max} determined by the fall-off of the electron number density.

For each value of L, we have next integrated P_2 over λ and ϕ, $P_3(L) = \int d\lambda \int d\phi\ P_2(L,\lambda,\phi) \cos^7 \lambda$. The $\cos^7 \lambda$ is the proper volume weighting factor. Because of the symmetry of our model only the single octant $0 \leq \lambda \leq \pi/2$, $0 \leq \phi \leq \pi/2$ need be considered. Convergence at large λ results dominantly from the strong peaking of j at the magnetic equator. In Figure 2, Curve 1 depicts as a function of L the total radiation intensity $P(L)=.1\ L^2 P_3(L)$ in Watts/(Hz steradian) emitted in the direction of the Earth by all the electrons in a dipole L shell of equatorial thickness .1 R_J; the Iowa electron model has been assumed to be applicable from $T=0$ to $T=\infty$. The inflection in the region $L=3.1-3.5\ R_J$ is a recurrent feature and is due to the complicated interplay of a) the radial dependence of the electron model (cf. Table 1), b) the drop-off with L in the dipole magnetic field strength, and c) the increase with L of the volume of a 0.1 R_J thick dipole drift shell.

The intensity in f.u. (1 f.u. = 10^{-26} Watts/m^2-Hz) received at Earth at a distance 4.04 A.U. from Jupiter is obtained by integrating $\int_{2.9}^{4.9} dL\ P(L)$ and multiplying by 2.8×10^{-24} ster./m^2. For Curve 1 the result is 21.4 f.u.

By contrast, the flux intensity from Jupiter's entire magnetosphere has been measured radio-astronomically by Slee and Dulk (1972) to be 6.0 ± 0.7 f.u. at 80 MHz. (A value of 4.5 ± 1.0 f.u. was previously reported by Gower (1968) at 81.5 MHz, but Slee and Dulk point out that the Gower observation is plagued by the presence of radiation from extra-Jovian sources). Even neglecting the strong magnetic field region $L<2.9\ R_J$, we come up with a value based on the model electron flux which is 3.5 times larger. The discrepancy is the more disturbing when one appreciates that the radio-astronomical error estimates are <25% at these frequencies.

Obscuration of portions of Jupiter's magnetosphere by the planet has been neglected in Figure 2. We have roughly evaluated this effect and find that it leads to a reduction of $\int PdL$ by less than 10%.

We have noted that a large portion of the radiation at 375 cm is produced by <10 MeV electrons, i.e., by electrons in the energy regime where the Iowa model is unverified. This situation at 375 cm is in contrast with that at 10.4 cm, where we found previously (Northrop and Birmingham, 1974) that scarcely any synchrotron radiation was produced by such low energy electrons. To assess quantitatively the effect of low energy electrons we ran two further cases, one in which the Iowa model, Eq. 3, was abruptly truncated so that no electrons existed below 5 MeV and a second in which the cut-off was taken to be 10 MeV. Curves 2 and 3 are the results. The discrepancy among the three curves is most pronounced at the smallest values of L, where the strongest magnetic fields exist and hence where the lower energy electrons can radiate most effectively.

Curves 2 and 3 correspond respectively to intensities of 13 f.u. and 4 f.u. at Earth. The lower value is compatible with Slee and Dulk's (1972) 6 f.u. if one assumes that an extra 2 f.u. comes from the Jovian magnetospheric region $L<2.9\ R_J$ unexplored by Pioneer 10.

To us, Figure 2 plus the Slee and Dulk radio observations are convincing evidence that there are active in the Jovian magnetospheric region $L<5\ R_J$

processes which diminish greatly the flux of $T < 10$ MeV electrons. We have no idea at the present time what such processes might be. A similar low energy cut-off was postulated by Gleeson et al (1970) on the basis of their attempted theoretical fit to the complete frequency spectrum of Jupiter's synchrotron emission.

The possibility that our naive magnetic field model might be at fault can be eliminated: we find that Curve 1 scales as approximately B^2 (Curves 2 and 3 are much less sensitive). Tilting the dipole by 10° while maintaining fixed x, y, and z axes in Fig. 1 leads to a <u>maximum</u> change in $|\underset{\sim}{B}|$ of $\sim 13\%$ at a fixed spatial position and hence to a maximum 25% change in Curve 1. (The variations of flux density with System III longitude measured by Slee and Dulk (1972) are 25%-type variations and lend credence to this estimate.) Offsetting the dipole by $|\Delta \underset{\sim}{r}| \simeq .1\ R_J$ leads to additional corrections of order $\frac{.1}{3} \sim 3\%$ which are yet smaller. We therefore do not see that use of a more refined model (Smith et al. 1974, Acuna and Ness, 1975) of Jupiter's magnetic field will substantially change our conclusions.

Finally, we remark that although experimental uncertainties are large close in to Jupiter, Pioneer electron experiments have noted either a leveling off (McIlwain and Fillius, 1975) or even an erosion (Fillius et al, 1975; Van Allen et al, 1975) of the differential flux in the <10 MeV region.

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Figure Captions

1. The model on which this calculation is based. Jupiter's magnetic field is that of a planet-centered dipole perpendicular to the line of sight from Earth. It has an equatorial surface strength of 4 Gauss. An electron at position L, λ, ϕ with local pitch angle δ and kinetic energy T is radiating. The intensity received from this electron is a sensitive function of θ, the angle between the line of sight and the local magnetic vector $\underset{\sim}{B}$.

2. The synchrotron flux P in Watts/(Hz-steradian) emitted in the direction of Earth by electrons in a dipole flux shell of equatorial thickness 0.1 R_J at a distance L in R_J from the center of Jupiter. Curve 1 includes electrons of all energies; Curve 2 is the radiation only from electrons with energy >5 MeV; and Curve 3 is the radiation only from electrons with energy >10 MeV.

Table 1 Parameters of the Iowa Electron Model

L (in R_J)	$K(m^{-2}sec^{-1})$	Γ	n
2.9	1.38×10^{14}	2.00	11.31
3.1	1.08×10^{14}	1.91	8.18
3.3	1.12×10^{14}	1.93	6.44
3.5	7.52×10^{13}	1.84	5.43
3.7	6.44×10^{13}	1.84	4.83
3.9	6.36×10^{13}	1.89	4.46
4.1	6.23×10^{13}	1.93	4.23
4.3	6.26×10^{13}	1.97	4.07
4.5	6.08×10^{13}	2.02	3.97
4.7	5.96×10^{13}	2.06	3.91
4.9	5.93×10^{13}	2.11	3.86

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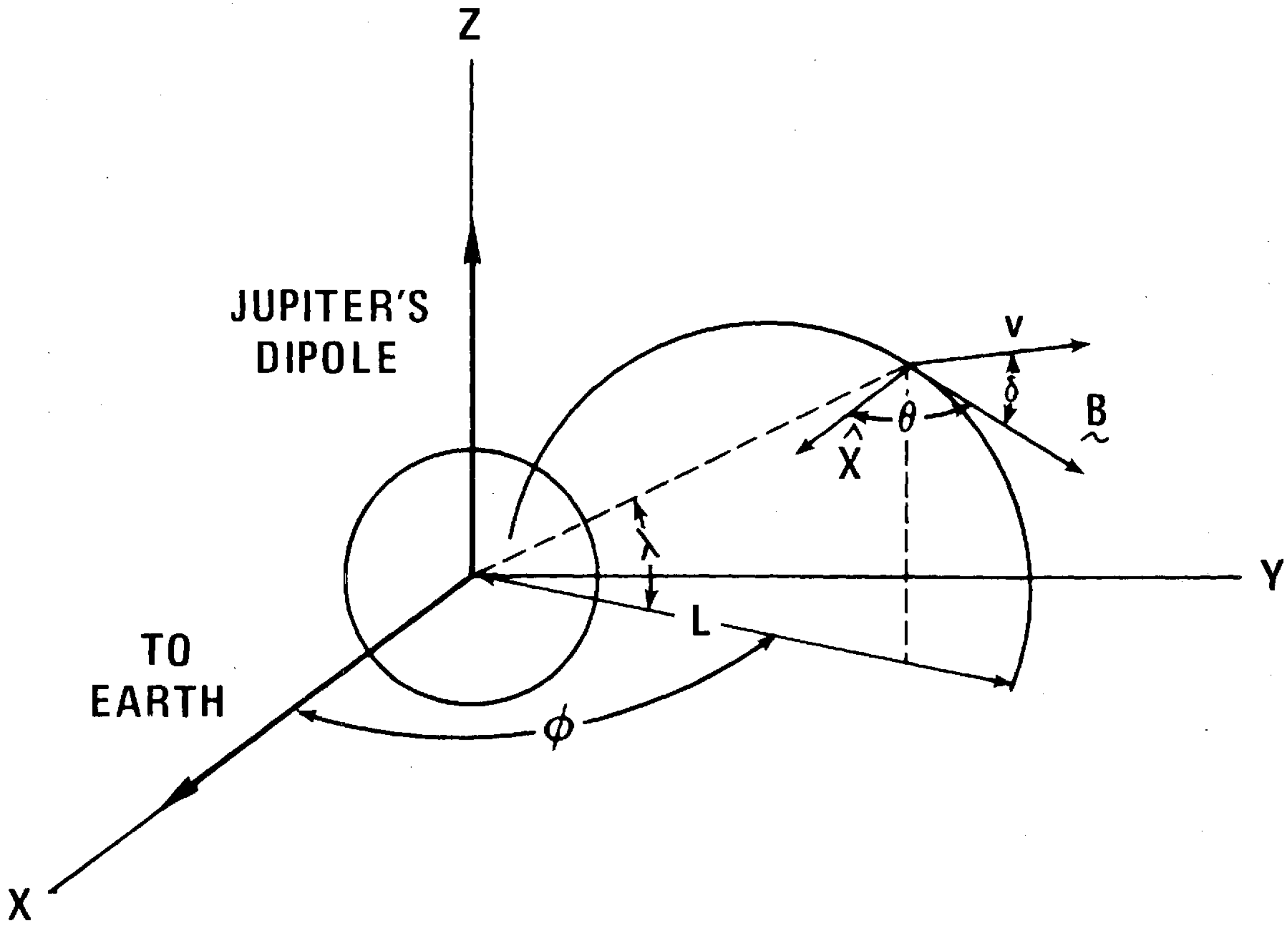
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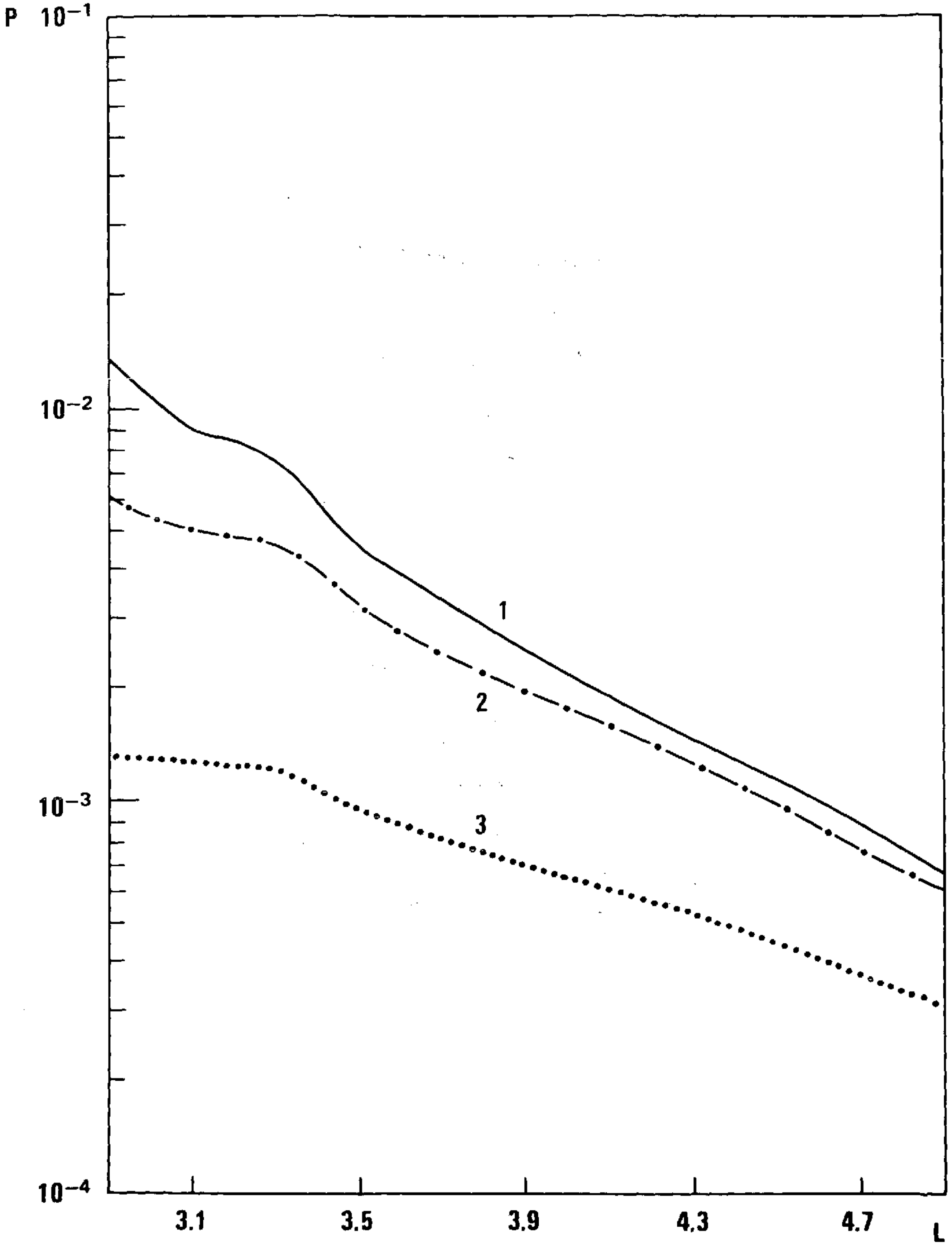
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