Reports

Asteroidal Source of Meteorites

Abstract. *The evolution of asteroidal orbits initially near the Kirkwood Gap at the 1:2 commensurability with Jupiter's period provides a mechanism for the production of meteorites from the asteroid belt without excessive velocity change. The resulting yield (~ 10^9 grams per year) and the orbital elements of Earth-crossing objects are in agreement with observational data on meteorites.*

Meteorites are the oldest known rocks. Their ages range from 4.5×10^9 to 4.7×10^9 years, and they provide a record of the formation of the solar system. Because we do not have definite knowledge of the source of the meteorites, their usefulness in enabling us to understand the origin of the solar system has been impaired. In recent years the asteroids have been considered the most likely source of meteorites, primarily on the basis of rather inconclusive mineralogical evidence. It is difficult, however, to find a mechanism that will transfer an object from an orbit lying wholly between Mars and Jupiter into one crossing that of Earth. Collision fragments with the necessary velocity change ($\sim$5 km/sec) would be in the form of fine dust or glass spherules. In contrast, most meteorites are relatively unshocked.

Previously proposed mechanisms for accomplishing the required orbital change have included perturbations by Mars of objects in orbits initially either Mars-crossing or located just beyond the orbit of Mars, as discussed by Öpik (*1*), Anders (*2*), and Arnold (*3*). These mechanisms are feasible, but the time scale of 10^9 years required to complete the orbital change is much longer than the observed cosmic-ray exposure ages of stone meteorites and is also long as compared to the probable collision lifetime of stone meteorites. This mechanism may be important for some iron meteorites. Periodic comets and their dead cores, as proposed by Öpik (*4*) and Wetherill (*5*), fulfill the dynamic requirements of a meteorite source. In addition, the ablation characteristics of the Taurid meteors (derived from Encke's comet) observed by the Prairie Network (*6*) suggest that these objects could survive penetration of Earth's atmosphere if their perihelia were near that of Earth and they consequently had relative velocities of $\sim$15 km/sec. However, before abandoning the asteroid belt as a source of at least some classes of stone meteorites, we felt it worthwhile to examine more subtle mechanisms for achieving the necessary orbital changes. One such mechanism is reported here. It appears to be an effective way to place asteroidal fragments into Earth-crossing orbits.

An asteroid in an orbit of semimajor axis a of about 3.27 astronomical units (A.U.) (the semimajor axis of the orbit of Earth), corresponding to the most apparent Kirkwood Gap, has a period almost exactly half that of Jupiter and will experience strong resonant perturbations by Jupiter which tend to decrease its perihelion and increase its aphelion over one half of the resonant cycle. This resonance by itself is, however, insufficient to perturb an asteroid into an Earth-crossing orbit. The orbital plane of the object will precess in space in such a manner as to avoid those close approaches to Jupiter that will suffice to make the orbit become Earth-crossing. This "libration" causes the angle

$$\theta = \lambda - 2\lambda_J + \omega$$

to avoid the value 180°, where λ and λ_J are the mean longitudes of the object and Jupiter, respectively, and ω is the longitude of perihelion of the orbit of the object.

In the proposed mechanism, fragments 10 to 500 m in diameter resulting from collisions between asteroids located just outside the region in which libration takes place are injected with velocities of 50 to 200 m/sec into the Kirkwood Gap. In addition, some small bodies could have remained in the libration region since the formation of the solar system. In either case, resonant perturbations by Jupiter will cause small initial values of the eccentricities e of such orbits to build up to values of about 0.3 to 0.4. These objects are commonly locked in the libration relationship so that approaches to Jupiter closer than 1.5 A.U. are prevented. Because the collision lifetime of fragments of this size is less than the age of the solar system (*7*), a second collision will subsequently occur between a librating object and either another librator or a ring asteroid, and the librating relationship will be destroyed, but the aphelia of the resulting fragments will still be great enough to permit close approaches to the orbit of Jupiter. These close approaches will generally occur near the aphelion of the fragment and will cause its perihelion to change more than its aphelion. The resulting "biased random walk" will slowly decrease the semimajor axis of the orbit an average of

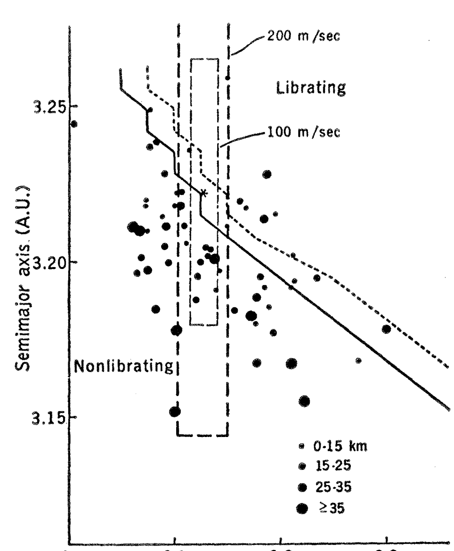

Fig. 1. A map of the librating region for semimajor axes less than the 1:2 resonance with Jupiter. Objects with a and e placing them below the solid diagonal line do not librate, whereas those above the dashed diagonal do, in general, librate. Because of the discrete nature of the calculation of the boundaries, we can say nothing about objects falling between the diagonal lines. The rectangular boxes centered on the asterisk at a = 3.223 A.U. and e = 0.125 show the maximum changes in a and e that can be produced by the indicated velocity increments. The approximate radii and locations of numbered asteroids near the boundary are also indicated.

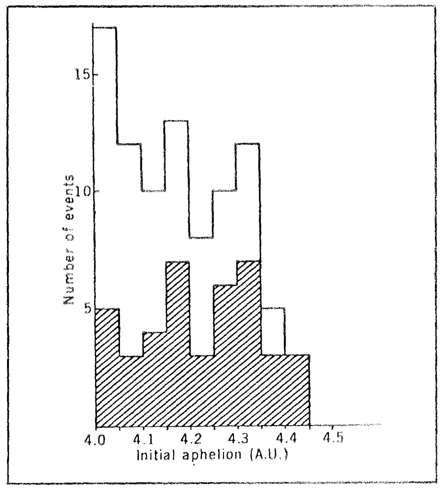

Fig. 2. The results of long-term integrations of the orbits of ejecta derived from our PLS source model. The outer envelope of the histogram shows the number of initial fragments by initial aphelion; the number of those objects becoming Earth-crossing in less than 10^5 years is represented by the shaded region.

about 0.01 A.U. per encounter. Simultaneously, the eccentricity will tend to increase in such a manner that the perihelion slowly descends while the aphelion remains nearly constant and less than 4.8 A.U. Ultimately, the orbit will become Earth-crossing when one node is in the plane of the orbit of Earth. The initial Earth-crossing orbits which are obtained from this mechanism have low inclination ($i \sim 5°$ to $10°$), high eccentricity (0.6 to 0.7), and semimajor axes between 2.4 and 2.8 A.U. Wetherill (*5*) has shown that these initial orbits will evolve in such a way as to be consistent with the data obtained from the Prairie Network as well as with the observed times of fall (*8*) and radiant directions (*9*) at the time of impact with Earth.

Figure 1 shows the approximate lower boundary of the region in *a-e* space in which libration tends to occur, together with the locations of the numbered asteroids in the region. The boundaries of the libration region shown in Fig. 1 are for orbits inclined 15° to the plane of the orbit of Jupiter, and the precise border is a function of inclination. Moreover, the eccentricity of the Jovian orbit further reduces the number of asteroids which strictly librate even though experiencing strong resonant perturbations.

A few orbits typical of fragments ejected from the libration region were numerically integrated; two objects became Earth-crossing in less than 10^4 years. In order to calculate enough orbits to estimate the yield of the proposed source mechanism, we used a more approximate but very much faster method. An interpolation based on the solutions obtained by Kozai and by others (*10, 11*) for the free oscillations in eccentricity and inclination was first calculated. The oscillations in eccentricity vary with the cosine of twice the argument of perihelion of the orbit of the object, and inclination is obtained by conservation of the component of angular momentum perpendicular to the plane of the orbit of Jupiter. This approximation was combined with fits to previously calculated solutions for the secular perturbations as obtained by Williams (*11*). During oppositions which produced encounters with Jupiter at distances of less than 1.35 A.U., numerical integration was used, with new approximations to the free oscillations and the Williams theory being calculated for the new orbit. Although this method does not provide accurate orbits for a specific object, it is valid for the analysis of an ensemble of orbits.

Initial orbits were derived from fragments ejected from within the libration region at random times with randomly directed velocities between 100 and 200 m/sec. These bodies would, at most, be lightly shocked, which is consistent with observations of meteoritic specimens. Two kinds of sources were chosen: a model distribution based on the objects observed in the Palomar-Leiden survey (PLS) (*12*) as being within the Kirkwood Gap, and the orbit of (1362) Griqua, the largest object known to librate (radius ~ 13 km calculated on the basis of an assumed albedo of 0.07) when it is at or near its maximum eccentricity as calculated by Marsden (*13*).

About 10 percent of the ejecta from both sources had aphelia between 4.0 and 4.8 A.U. and were also outside of the librating region. The results of the calculation showed that 28 ± 7 percent of the fragments derived from Griqua became Earth-crossing within 10^5 years. Orbits were followed for 90 objects derived from the PLS distribution, and, of this group, 45 ± 7 percent of the orbits became Earth-crossing in less than 10^5 years. The results of this set of calculations are shown in Fig. 2.

Calculation of cratering yields, according to a method used earlier (*14*), indicates $\sim 3 \times 10^{11}$ g/year of material will be injected into the gap by cratering from each object of 30-km radius near the gap. The injected mass varies as $R^{2.5}$, where R is the radius of the source object, and, as can be seen from Fig. 1, there are many objects at least that large in the vicinity of the gap. Similar calculations based on the number of asteroids in the gap, as found by the PLS, when corrected for the incompleteness of the survey, indicate an ejection rate from the gap of (dM_e/dt) $\sim 10^{13}$ g/year. Within the limits of the accuracy of these calculations, the population of small bodies within the gap could be in a steady state, mainly derived from sources not in the gap, or could be partly residual material from the formation of the solar system. This result can be used to estimate the yield (dM_m/dt) of meteorites at Earth.

This yield will be:

$$\frac{dM_m}{dt} = Y_e \times \frac{dM_e}{dt} = Y_e \times 10^{13}\ \text{g/year}$$

where Y_e, the yield fraction, may be represented as the product of: Y_1, the fraction of fragments of meteorite size with velocity between 100 and 200 m/sec (~ 5 percent) (*15*); Y_2, the fraction with acceptable aphelia but not librating (10 to 15 percent); Y_3, the fraction becoming Earth-crossing with aphelia ≤ 4.8 A.U. (45 ± 7 percent); and Y_4, the fraction impacting Earth (2 to 3 percent). Earlier unpublished Monte Carlo calculations give ~ 2 percent for the last factor, but the forced oscillations tend to prevent some close encounters with Jupiter, possibly increasing the lifetime in Earth-crossing orbits before Jupiter either collects or rejects the object, thus increasing the probability of capture by Earth. In addition, many ejecta fragments have satisfactory aphelia but lie within the librating region. Because of the eccentricity of the Jovian orbit, some of these will certainly not librate and will be able to encounter Jupiter. This can increase Y_2. The ejection rate (dM_e/dt) calculated is based on the observed number of PLS asteroids in the resonant region and does not depend on the computation of the injection rate.

A low estimate of Y_e is thus 4×10^{-5}, and a high estimate is 12×10^{-5}. A likely intermediate value may be 8×10^{-5}. Multiplication of this value of Y_e by (dM_e/dt) thus places the probable flux of meteorites derived from the 1 : 2 resonance with Jupiter in the asteroid belt at 8×10^8 g/year. This result is similar to the observational estimate of 10^9 g/year obtained by Hawkins (*16*) as well as that obtained by Latham *et al.* (*17*) from lunar seismic data, although the flux obtained by the Prairie Network (5×10^{10} g/year) from all sources, including fireballs (*18*), is higher. Including uncertainties in (dM_e/dt), there may be an uncertainty of an order of magnitude in our calculations; however, the resonant extraction mechanism we propose should result in a significant meteorite flux at Earth.

Spectrophotometric study (*19*) of asteroids such as (511) Davida, (814) Tauris, (31) Euphrosyne, (175) Andromache, and (108) Hecuba lying near the boundary of the Kirkwood Gap could permit their identification with known classes of meteorites. Another asteroidal resonance extraction mechanism, utilizing "secular" resonances rather than commensurabilities, has recently been proposed by Williams (*20*) and may be of comparable importance.

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21. We thank Dr. J. G. Williams for his continuing assistance and especially for providing several computer subroutines and his unpublished data. We also thank J. G. Higdon for writing some computer programs used in this work. Research supported by NASA grant NGL-05-007-005.
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18 June 1973

An Atmosphere on Ganymede from Its Occultation of SAO 186800 on 7 June 1972

Abstract. *On 7 June 1972 the third Jovian satellite Ganymede occulted the eighth-magnitude star SAO 186800. Successful photoelectric observations obtained at Lembang, Java (Indonesia), and Kavalur, India, show nonabrupt immersions and emersions, indicating the presence of an atmosphere whose surface pressure is greater than about 10^{-3} millibar. By fitting the two occultation durations as chords to a model disk, the diameter is found to be 5270 (+30, $-\sim$200) kilometers, the major error contribution arising from the uncertain atmospheric thickness below the occultation layer. The derived mean density is 2.0 ($-$ 0.03, + $\sim$0.2) grams per cubic centimeter.*

A search for occultations of stars by planets carried out by Taylor at the Royal Greenwich Observatory indicated that the star SAO 186800 (magnitude 8.0, type K0) would be occulted by Ganymede (JIII) on 7 June 1972 (*1*). The predicted intensity drop was about 5 percent at visible wavelengths.

Since the stellar position was the largest single source of error in the predictions, photographs taken in March 1972 at the observatories at the Cape of Good Hope, South Africa, and Perth, Australia, were analyzed to yield more accurate relative positions of Ganymede and the star. The predictions were accordingly refined. The predicted area of visibility included southern Asia, northern Australia, and eastern Africa. The uncertainty in the relative position of the two bodies was then estimated as 0.3″. The adopted diameter for prediction purposes was 5550 ± 130 km (*2*).

Successful observations of the occultation were made by Hidayat, Carlson, and Johnson at the Bosscha Observatory near Lembang, Java, and by Bhattacharyya at the Kavalur field station of the Kodaikanal Observatory in India. B. A. Smith and S. A. Smith, observing with a portable photometer and 20-cm telescope from Darwin, Australia, were just slightly (50 km; see Fig. 1) south of the actual occultation zone and obtained negative results. The sky was of excellent photometric quality with scintillation noise below average and all equipment functioned properly. An attempt was also made by S. D. Sinvhal at the Uttar Pradesh Observatory in Naini Tal, India, with photoelectric equipment but the fluctuations in sky transparency were too large for any events to be detected.

The photoelectric observations of the event from Lembang (107.6°E, 6.8°S, 1300 m above sea level) were made with the Bosscha twin 60-cm refracting telescopes mounted in the same tube. The sky was clear and of excellent photometric quality. Measurements were obtained with a two-channel photometer, one channel for the red [wavelength (λ) $\gtrsim$ 6000 Å] and the other for the blue ($\lambda \lesssim$ 4500 Å), with cooled photomultipliers and pulse-counting electronics. Only the data from the red channel, which were of higher quality, are reported here. The accumulated counts (at a sampling rate of 22.25 $\sec^{-1}$) were displayed on a visual readout and recorded with a 16-mm cine camera operated at a framing rate of about 24 $\sec^{-1}$. Also photographed was the display from an accurate quartz oscillator referenced before and after the event to radio station WWV by using an observatory chronometer. The absolute accuracy of the timing is estimated to be ± 1 second; the relative accuracy during the event was ± 0.1 second. Dead-time corrections of approximately 25 percent have been applied to the data. Direct photographs of the event were also taken and have been published elsewhere (*3*). The photoelectric tracing obtained at Lembang is shown in Fig. 2. The immersion and emersion midpoint times are 18^h47^m-$40.9^s \pm 1.2^s$ and $18^h50^m22.4^s \pm 1.2^s$ in corrected universal time (U.T.C.).

The observations at Kavalur (78.7°E, 12.6°N, 800 m above sea level) were