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Radar observations of the Arietids

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ABSTRACT

Results from three years of radar observations of the Daytime Arietid meteor shower are presented. The CMOR meteor radar was used to measure the radiant and pre-atmospheric speed of the shower, from which an orbit has been calculated. The integrated fluence of the Arietid shower is very high relative to other meteor showers.

Key words: techniques: radar astronomy – meteors, meteoroids.

1 INTRODUCTION

The Arietids are almost certainly the shower with the highest cumulative activity of the year. The peak rates of the Arietids are comparable to those of better known showers like the Perseids and Geminids, but the Arietids produce significant activity over a longer period. In spite of this, the Arietids remain one of the least characterized of the major showers, because they occur during daylight hours. Radar observations of the Arietids have been done, but because of the difficulty in measuring speed and radiants from radar observations, the values show much scatter. This paper will attempt to address the lack of knowledge about the Arietids, using radar observations carried out with the Canadian Meteor Orbit Radar (CMOR), located near Tavistock, Ontario in the years 2001, 2002 and 2003.

The Arietids went undiscovered until the advent of radar studies, when it was quickly recognized that significant meteor activity occurred in the daylight hours each June. While strong radiants in Perseus and Aries were observed in 1947 and 1948 (Clegg, Hughes & Lovell 1947; Aspinall, Clegg & Lovell 1949), the Arietids were not properly identified until 1951 (Aspinall & Hawkins 1951). Part of the difficulty with isolating the Arietids is due to the close proximity of the zeta Perseid shower, which is weaker than the Arietids but still very significant. Measurements of the radiant, speed and orbit of the Arietids from previous studies are shown in Table 1.

The speed measurements in each of the studies were done using the Fresnel diffraction technique, in which the oscillations of the meteor echo are measured to determine how long it takes to cross the Fresnel zones. This technique is very accurate, but it only works for a small fraction of echoes; in the other cases, fragmentation of the meteoroid obscures the oscillations. This may result in biased measurements.

In earlier Jodrell Bank studies (Aspinall et al. 1949; Aspinall & Hawkins 1951), radiants were determined using a steerable beam. Later studies at the same facility (Almond 1951; Davies & Greenhow 1951; Lovell 1954; Davies & Gill 1960) used a four-element interferometer to obtain radiants for individual echoes using the Fresnel speed. Interferometry was also used by Nilsson (1964) and Gartrell & Elford (1975) to obtain radiants. Most of the observations were carried out on the indicated solar longitude, but Aspinall & Hawkins (1951) observed throughout June and found an average change per day of $\Delta\alpha = 0\overset{\circ}{.}75$ in right ascension and $\Delta\delta = 0\overset{\circ}{.}9$ in declination. This accounts for some but not all of the observed radiant scatter.

Errors in measurements of the radiant and speed produce different orbits for each study: the semimajor axis and the inclination show particular scatter. It is of great interest to reduce the errors in the observed quantities, so that a more accurate orbit might be calculated.

2 OBSERVING EQUIPMENT AND PROCEDURES

Observations of the Arietids were collected as part of the standard operation of the CMOR meteor patrol radar located near Tavistock, in Ontario, Canada ($80\overset{\circ}{.}772\ W$, $43\overset{\circ}{.}264\ N$). Details of the system are given in Jones et al. (2004); a brief description is given here. The radar consists of three complete meteor radars, each with a peak power of roughly 6 kW, operating at 17.45, 29.85 and 38.15 MHz. Only the 29-MHz system was used in the current study: the 17-MHz system suffers from severe interference during daylight hours in the summer, and the 38-MHz system is more affected by initial radius, and therefore produces fewer data. The basic configuration is backscatter, with five receiver antennas acting as an interferometer to provide the altitude and azimuth of any received echo, to a precision of about 1°. With the range information, this is sufficient to determine the height of the echo, although not the radiant, as the exact orientation of the trail is not known.

The 29-MHz system is equipped with two remote receivers, in addition to the five interferometer receivers, which are located 8.1 and 6.2 km from the transmitter, and aligned at an angle of $96\overset{\circ}{.}8$ to each other. These can be used to measure time-of-flight velocities and radiants. Unlike the commonly used method of Davies & Gill (1960), where the Fresnel speed is used with the time of flight captured by the outer stations to determine the radiant, the CMOR system uses the radiant as determined by the interferometer to calculate the speed. For more details, see Jones et al. (2004).

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Table 1. Arietid data from previous studies. α and δ are in degrees, pre-atmospheric speed is in km s^{-1}, a, q and Q are in au, and i, ω and Ω are in degrees. (1) and (2) refer to different radiants associated with the Arietids observed by some groups.

Study	α	δ	v	a	e	i	q	Q	ω	Ω
Aspinall et al. (1949)	40	+22								
Almond (1951)	44.3	+22.6	37.7	1.5	0.94	18	0.10	2.90	29	77
	±1	±1.5	± 4.3	±0.7	±0.04	±5	±0.03	±1.4	±2	
Davies & Greenhow (1951)			38.5							
			± 2							
Lovell (1954)(1)	43.7	+24.5	38.7	1.6	0.94	21	0.09	3.1	29	76.8
			±4.4		±0.04	±8	±0.03		±3	
Lovell (1954)(2)	46.0	+22.4	38.5	1.6	0.95	13	0.09	3.1	29	77.5
			±3.2		±0.03	±4	±0.02		±2	
Davies & Gill (1960)	50	+26	41	1.33	0.97	46	0.04	2.62	19	89
Nilsson (1964)(1)	46.6	+25.0	43.6	2.27	0.98	38.9	0.06	4.48	20	84.6
	±0.4	±0.7	±0.6							
Nilsson (1964)(2)	46.1	+26.1	39.6	1.50	0.96	33.4	0.06	2.94	23	84.8
	±1.1	±0.8	±1.1							
Baker & Forti (1966)	36	+26	38	2.78	0.93	31.3	0.09	5.47	27	73
Kashcheev & Lebedinets (1967)(1)	43	+23	39	1.67	0.94	18.7	0.10	3.24	30	77
Kashcheev & Lebedinets (1967)(2)	52	+25	40	1.67	0.96	22.8	0.08	3.26	25	87
Gartrell & Elford (1975)	49	+23	41	2.77	0.96	17.4	0.04	5.50	18	82
Current study	43.0	+26.4	39.4	1.64	0.944	28.2	0.0928	3.19	29.4	78.5
	±2.3	±1.3	±1.1	±0.24	±0.013	±4.0	±0.013	±0.48	±1.9	

The power on each of the three system is monitored continuously, so that fluctuations in power due to module failures etc. can be taken into account when measuring meteor rates. The power was fairly constant near 6 kW in 2001 and 2002, but data are missing from June 8 to June 12 in 2003, so those rates are excluded from the analysis.

One thing that cannot currently be measured accurately by the Tavistock radar is the mass distribution index of a meteoroid population. The echo detection software filters out overdense echoes, and there is insufficient range between the limiting sensitivity and the overdense limit to produce a measurable slope. This limitation of the radar could be remedied either by modifying the meteor detection software to include overdense echoes, or by increasing the transmitter power to give a larger dynamic range of underdense masses.

3 RADIANT POSITION AND MOTION

The Arietid radiant position was measured using a single-station method, which allowed all single-station meteors to be used, and not only the brighter meteors observed at both remote stations, similar to the single-station radiant mapping procedure described in Jones & Morton (1977). Since reflection from meteor trains is a specular process, echoes are always observed when the meteor train is at right angles to the radar observing direction; each echo is thus 90° from the radiant. For an individual echo, it is not possible to determine the radiant more precisely than a great circle, on which the radiant is located; but the number of echoes belonging to particular radiants can be estimated. The procedure is to count, for every possible radiant, the number of echoes that fall on a strip 3° wide along the echo line. This procedure allows contamination of a source with sporadic meteors, since some of these will by chance fall on the echo line of the source. To account for this, a weighted function is used which subtracts meteors that are slightly more than 3° from the echo line. Ideally, as many sporadic meteors will fall in this region as on the echo line of the source, so the final value should be the number of shower meteors. This technique has been found to locate all major shower radiants accurately. A sample plot of radiants is given in Fig. 1.

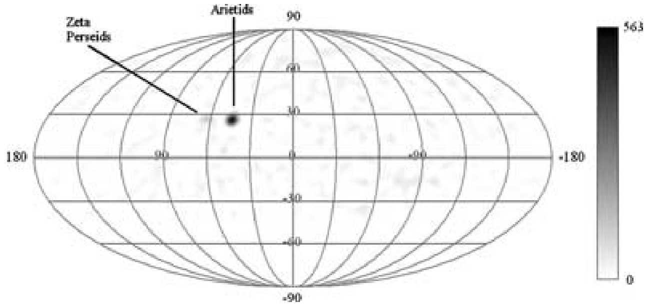

Figure 1. Distribution of radiants for 2001 June 6. Note the zeta Perseid radiant to the left of the prominent Arietid radiant.

The position of maximum activity was measured on similar maps between May 30 and June 22 for 2001, 2002 and 2003.

The motion of the radiant for all three years was calculated. The right ascension was found to be

$$\alpha = -15.096 + 0.738\lambda \tag{1}$$

degrees (where λ is the solar longitude), with an estimated error of $2\overset{\circ}{.}3$. The declination was

$$\delta = 9.064 + 0.220\lambda \tag{2}$$

degrees, with an error of $1\overset{\circ}{.}3$. This is valid between 68° and 91° solar longitude, and corresponds to $\alpha = 44\overset{\circ}{.}0$ and $\delta = 26\overset{\circ}{.}6$ at the peak solar longitude, $78\overset{\circ}{.}5$.

4 FLUXES

Fluxes were also calculated from single-station data, since these suffer less from observing effects. All echoes less than 3° from the echo line were initially accepted to calculate raw rates for each day. To calculate the actual flux, or number of meteoroids passing through a square kilometre of space in a 1-h interval, the area under observation must be calculated, and certain corrections applied. The collecting area of the radar is a strip of space which covers all points at 90° to the radiant, spanning a height interval dh where meteors occur, and extending down to an elevation of 20°. Echoes below this elevation are rejected, since at very large ranges it is not possible to determine the height unambiguously. The area of each section of this strip is weighted according to the gain of the transmitting and receiving antennas in the direction in question.

In order to calculate the collecting area (or for that matter any calculation where the sensitivity is changed), the mass distribution index must be known. We assume that the Arietid meteoroids follow a size distribution such that $dn \propto dm^{-s}$, where dn is the number of meteoroids with masses between m and $m + dm$, and s is the mass distribution index. For $s = 2$, the total mass of particles over any given size range will be equal. For $s < 2$, there is an excess of mass in large meteoroids, and for $s > 2$ an excess of mass in small meteoroids. The mass distribution index of the Arietids has been measured as 1.8 for bright meteors and 2.7 for faint meteors by Browne et al. (1957), and as varying between 1.7 and 2.7 (Elford 1968). A value of 2.1 (a slight excess of small meteoroids) was chosen for the flux calculations. The effects of varying s will be examined later.

A detailed explanation of the calculation of collecting areas is given in Brown et al. (1998). It involves integrating over the strip where echoes from the desired radiant are visible, taking into account the varying sensitivity of the antenna gain patten. The total collecting area will depend on the declination of the radiant, and quite strongly on the mass distribution index. Lower values of s translate into higher collecting areas (and therefore lower fluxes), while higher values produce smaller collecting areas. A factor of $\cos^{1.4} z$ (z is the zenith angle) is added after Bellot Rubio (1995), to account for observing biases at large ranges.

The raw flux obtained by dividing the observed meteor rate by the collecting area still has to be corrected for radar observing biases. The most significant bias is the initial radius effect (Campbell-Brown & Jones 2003), which greatly reduces the number of echoes observed at large heights when the radar frequency is of the order of tens of MHz. The fraction of echoes that are observed can be calculated at a particular observing frequency and meteor speed. The percentage of sporadic meteors detected can be found as

$$C = \left[1 + \exp\left(\frac{h_{\max}}{6.28} - \frac{\ln \lambda_{\rm r}}{0.770} - 12.4\right)\right]^{-1}, \tag{3}$$

where $\lambda_{\rm r}$ is the wavelength of the radar and $h_{\max}$ is the height at which most meteors are observed. This can be found by

$$h_{\max} = 99.6 - 1.77(lm - 9) + 9.86 \ln\left(\frac{v}{33.7}\right), \tag{4}$$

where lm is the radar limiting magnitude and v is the speed of the shower being observed. At 29 MHz, roughly 30 per cent of meteors with velocities of the order of 40 km s^{-1} are observed.

Finally, for reference, the flux is adjusted to a limiting magnitude of +6.5, from the radar's limiting magnitude of approximately +8.4. The corrected flux can be found using

$$N_{6.5} = N_{lm} \times 10^{(6.5 - lm)(s-1)/2.5}. \tag{5}$$

The exact limiting magnitude was calculated using the average power measured on that day by the power monitoring system on the radar. This step also requires an estimate of the mass distribution index: in this case, a higher s will yield a lower flux. The fact that the collecting area and limiting magnitude correction are influenced in opposite directions means that this corrected flux is relatively insensitive to changes in s.

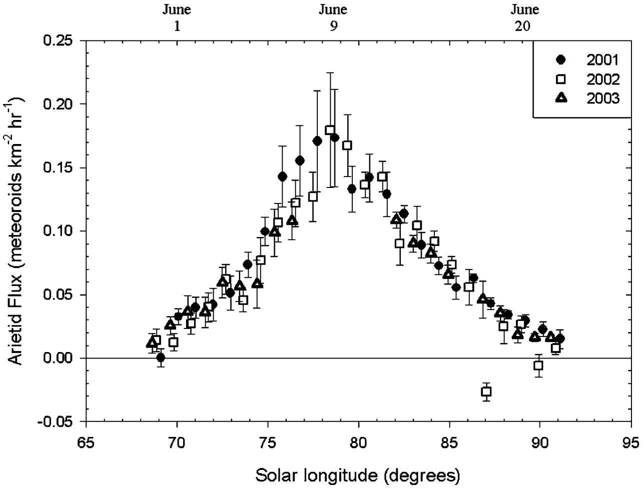

Figure 2. Flux of Arietids, of magnitude +6.5 or greater, in 2001, 2002 and 2003.

To account for sporadic meteors occuring by chance near the Arietid radiant, the same flux calculation was performed for the same radiant on five non-shower days in late June, and the average of this background rate was subtracted from the shower days.

The fluxes are plotted in Fig. 2. The flux can be converted to a zenithal hourly rate, or ZHR, for comparison with other showers:

$$\mathrm{ZHR}_{\rm obs} = \frac{37\,200\Phi(r - 1.3)^{-0.748}}{13.10r - 16.45}, \tag{6}$$

where r is the population index, which can be found from the mass distribution index with

$$r = 10^{(s-1)/2.5}. \tag{7}$$

The maximum flux of 0.17 meteoroid km^{-2} d^{-1} corresponds to a ZHR of approximately 200, comparable to the Quadrantids. It should be emphasized that when a more accurate value of the mass distribution index is obtained, the ZHR could change dramatically. For example, an s of 1.7 would increase the collecting area by a factor of 2.2, the flux corrected to +6.5 mag is 95 per cent of the flux with $s = 2.1$, and the ZHR would increase by a factor of 4.3. For an s of 2.7, the collecting area is reduced by a factor of 4, the corrected flux increases by a factor of 1.3, and the ZHR is only 0.27 of that with $s = 2.1$.

The total fluence of Arietid meteoroids in a given year is about 1.7 meteoroid km^{-2}, to a limiting magnitude of +6.5, which corresponds to a mass of approximately 10^{-6} kg.

5 SPEED

In order to calculate accurate orbits, it is important to find the pre-atmospheric speed, prior to deceleration. To our knowledge, this has not previously been examined by radar for a known shower as a function of height. Examining the average speed for each of the two years (2002 and 2003) showed no significant differences between the two, so data from both years were combined. A plot of the average speed as a function of height clearly shows the decelerating effect of the atmosphere (Fig. 3). The functional form of the deceleration is not easy to obtain: like most faint meteors, Arietids probably fragment extensively, making the deceleration unpredictable even for a known initial mass. A second-order fit to the data was performed as

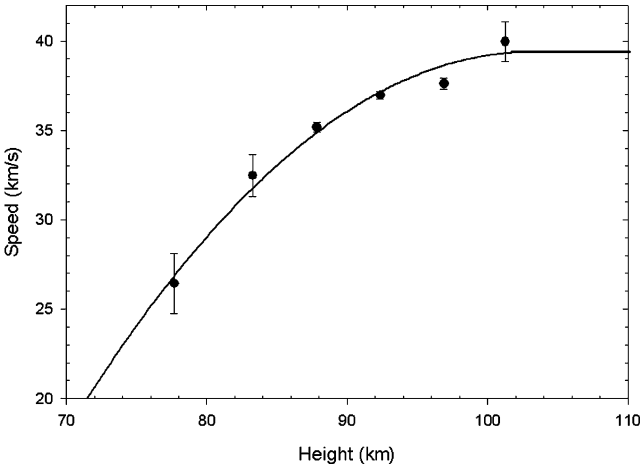

Figure 3. Average speed of Arietids in 2002 and 2003, plotted against height. A second-order regression provides an estimate of the pre-atmospheric speed.

the simplest way of judging the maximum speed. The peak of the fitted parabola is at 39.4 km s^{-1}, and this value was adopted for the current study.

There were not enough points in each day to determine any variation in speed as a function of solar longitude, so the average speed for each day was calculated in both years, to see if any variation could be detected in those profiles. There was a slight increase in speed with solar longitude, but it was not statistically significant, so a constant speed was adopted for the whole activity period.

6 ORBIT

Since the speeds measured for each meteor are subject to an unknown amount of deceleration, which most likely varies from meteor to meteor, the Arietid orbit was calculated using the extrapolated speed found in the previous section. Each parameter was calculated on days between May 30 and June 22, for which the radiant position had been measured: this gives a range for each parameter.

The error for each quantity was computed from the expected errors in the radiant position and the speed. The error in a (shown in Fig. 4) is of the order of 0.4 au; in e (Fig. 5) it is 0.015, making the variation in e negligible. The perihelion distance (Fig. 6) has error of the order of 0.014 au, and the aphelion distance (Fig. 7) has an error of 0.75 au. The error in the argument of perihelion (Fig. 8) is 2° and it is 3° for the inclination (Fig. 9).

The geocentric speed of the Arietids was found to be 37.6 km s^{-1}.

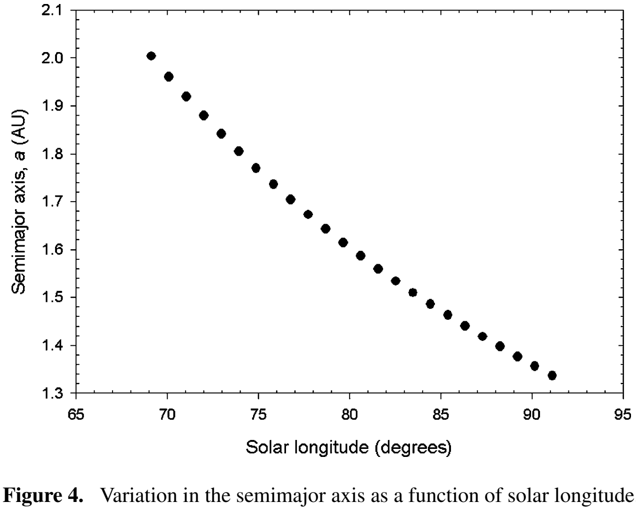

Figure 4. Variation in the semimajor axis as a function of solar longitude.

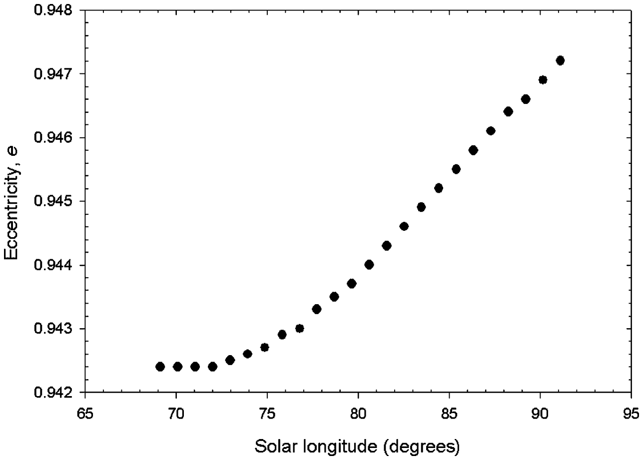

Figure 5. Variation in the eccentricity as a function of solar longitude.

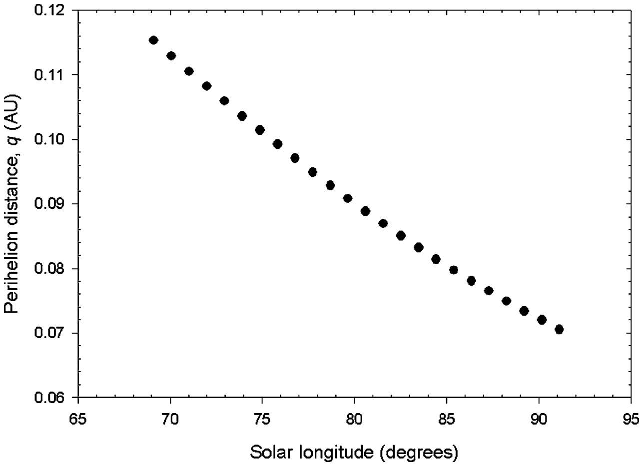

Figure 6. Variation in the perihelion distance as a function of solar longitude.

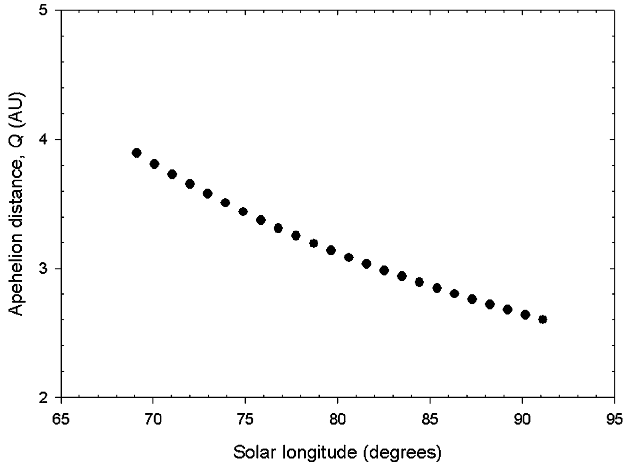

Figure 7. Variation in the aphelion distance as a function of solar longitude.

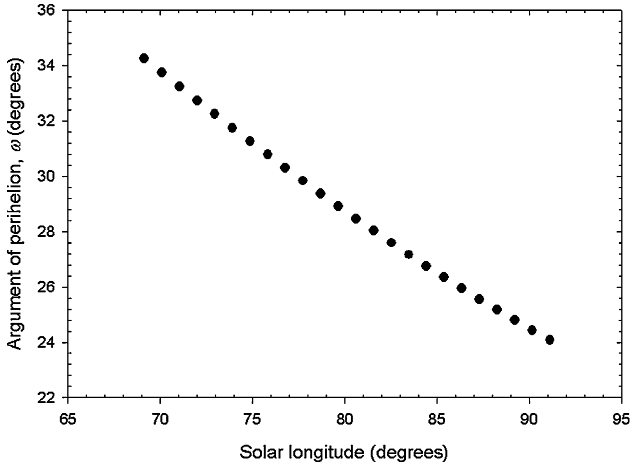

Figure 8. Variation in the argument of perihelion as a function of solar longitude.

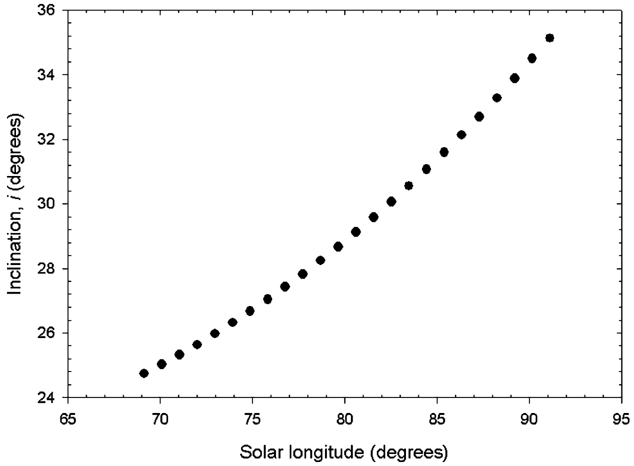

Figure 9. Variation in the inclination as a function of solar longitude.

7 CONCLUSIONS

The Arietids are responsible for one of the greatest fluences of meteor material from a single directional source over the course of any given year, cumulatively equivalent to the fluence from a short-duration Leonid meteor storm. The change in flux over time and the radiant motion are consistent from year to year.

It should be noted that no evidence was seen of smaller streams close to the Arietid radiant: such small associations of a few orbits have been noted by some investigators (for example Gartrell & Elford 1975). This may be due to the lack of resolution in the technique employed here, or may reflect the fact that the smaller associations are sporadic and cannot be observed every year.

The observed Arietid orbit changes significantly over the duration of the shower: this is to be expected. The Arietid stream must have a considerable spread in order to intersect the Earth's orbit over such a period. The inclination is particularly interesting, since there has been much discussion about the wide range of observed inclinations. Our observations suggest that *i* is near the upper range of previously determined values. The eccentricity is the only element that did not show variation over the shower duration greater than the error in the quantity.

Certain modellers (Babadzhanov & Obrubov 1992; Jones & Jones 1993) have linked the Arietid stream to Comet P/Machholz. The current study agrees well with modelled values published in Babadzhanov & Obrubov (1992), other than eccentricity (measured at 0.945, estimated in the model to be 0.96–0.99) and geocentric velocity (37.6 km s^{-1} versus the model values of 40–44 km s^{-1}). The model of Jones & Jones (1993) also matches well: in particular, the declination motion, which was thought to be poorly matched, has been measured at $+0\overset{\circ}{.}2$ per day, which compares favourably to the $0\overset{\circ}{.}1$ per day of the model. The radiant motion in right ascension is still significantly different: the model predicts $0\overset{\circ}{.}4$ per day, but we have measured $0\overset{\circ}{.}7$ per day. The same discrepancy in geocentric speed also exists in this model (43.1 km s^{-1}, compared with the measured 37.6 km s^{-1}).

The CMOR radar has enhanced our ability to measure shower radiants and orbits with great precision. In particular, the capacity of this radar to measure the orbits of meteor streams over many years should help to place constraints on models of their origins.

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