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A SEARCH FOR INTERSTELLAR METEOROIDS USING THE CANADIAN METEOR ORBIT RADAR (CMOR)

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Abstract. Using the CMOR system, a search was conducted through 2.5 years (more than 1.5 million orbits) of archived data for meteoroids having unbound hyperbolic orbits around the Sun. Making use of the fact that each echo has an individually measured error, we were able to apply a cut-off for heliocentric speeds both more than two, and three standard deviations above the parabolic limit as our main selection criterion. CMOR has a minimum detectable particle radius near 100 μm for interstellar meteoroids. While these sizes are much larger than reported by the radar detections of extrasolar meteoroids by AMOR or Arecibo, the interstellar meteoroid population at these sizes would be of great astrophysical interest as such particles are more likely to remain unperturbed by external forces found in the interstellar medium, and thus, more likely to be traceable to their original source regions. It was found that a lower limit of approximately 0.0008% of the echoes (for the 3σ case) were of possible interstellar origin. For our effective limiting mass of 1×10^{-8} kg, this represents a flux of meteoroids arriving at the Earth of 6×10^{-6} meteoroids/km^2/h. For our 2σ results, the lower limit was 0.003%, with a flux of 2×10^{-5} meteoroids/km^2/h. The total number of events was too low to be statistically meaningful in determining any temporal or directional variations.

Keywords: Interstellar, meteoroids, meteors, radar

1. Introduction

While previous experimental studies have provided flux estimates of interstellar particles (ISPs), they were limited to particles under 100 μm in radius. Flux estimates for larger dust in the interstellar medium (ISM) are unconstrained since there is no easy way to remotely sense the number density of these larger particles. The detection of such particles is also very important as larger particles are less likely to be perturbed by external forces found in the ISM, such as interstellar magnetic fields. This implies that they may be more readily associated with their original source regions or stars through back integration of their motion, and their larger sizes implies a longer survival time against collisions or shock disruption. This is important as the processes in which ISPs are produced and ejected into the ISM, particularly for larger particles, are not very well constrained. Knowing source regions, and the possible detection of streams of ISPs at the Earth (cf. Baggaley and Neslusan, 2002) would allow for direct sampling (through aerogel capture), which would give the first opportunity to investigate the chemical and isotopic signatures of ISPs with a known origin. Measuring the space density of the largest ISPs is also important for estimating the mass density and gas-to-dust ratio of the ISM proximal to the solar system as most of the mass of the dust grains in the ISM is expected to be contained in the largest grains (Landgraf et al., 2000). While we are measuring the larger grains in the local ISM, it is important to note that these grains are dynamically decoupled from the local interstellar gas flow and hence, not directly physically connected to the Local Interstellar Cloud (Kimura et al., 2003).

Here we examine the flux of ISPs visible from the northern hemisphere using an all-sky, VHF orbital radar.

2. Previous Studies

The first modern detection of ISPs in the solar system was made by Ulysses in 1992 (and later confirmed by Galileo) when it detected a flux of micrometre-sized dust particles (Grün et al., 1993) moving in a retrograde orbit with heliocentric speeds above the solar system escape speed at Jupiter (26 km/s). These detections were the first to prove definitively that some ISPs do enter the solar system.

A search for interstellar meteoroids was conducted by Baggaley (2000) using the Advanced Meteor Orbit Radar (AMOR) located in New Zealand. Baggaley claimed to be able to identify the existence of a dust influx from a widespread south-ecliptic latitude source as well as a discrete stream that he identifies as being in the direction of the main-sequence debris-disk star β-Pictoris. As well, there have been also been reported detections from Arecibo (Meisel et al., 2002).

Murray et al. (2004) on theoretical grounds, show that for such large particles as will be considered here (> 100 μm), the ISPs can travel for tens of parsecs through the ISM without having their paths altered. This allows their source regions to be determined. They also give a rough estimate to the flux of ISPs that are expected to be visible at the Earth, as both a function of mass, and particle size. For CMOR, a particle size of 100 μm (assuming a meteoroid density of 3000 kg/m^3) should have a detectable ISP flux of approximately 5×10^{-4} meteoroids/km^2/h, using a power-law relation extrapolated from the distribution of the largest mass ISPs detected by Ulysses and Galileo, as originally noted by Landgraf et al. 2000).

Hawkes and Woodworth (1997) used image-intensified camera systems to search for meteoroids of interstellar origin. Optical studies are advantageous in that the results are more accurate (due to a larger portion of the meteor trail being visible), however the number of detected events can be quite small. Out of 160 observations, they found that two events, with masses on the order of 10^{-7} kg, were of interstellar origin. This represents 0.01% of their total observations.

Hajduková (1994) made a detailed study of photographically determined meteor orbits found in various catalogues, and determined that almost all of the hyperbolic orbits (which amount to 12%) were potentially due to errors in determination of their heliocentric speeds. When the errors were taken into account, the actual fraction of photographically determined orbits that may be of interstellar origin was reduced to be at most 0.002%. It is clear from this, that proper error analysis is essential in identifying ISPs.

3. Instrumentation and Data

The Canadian Meteor Orbit Radar (CMOR) is 6 kW peak power HF/VHF meteor radar based on the commercially available SKiYMET system (Hocking, 2001). The system, located near Tavistock Canada (43.264° N, 80.772° W) has been modified to include two additional remote station receivers used for time-of-flight velocity measurements, and has a radio magnitude limit of $+8$, corresponding to an effective limiting mass of 4×10^{-8} kg at typical interplanetary meteoroid encounter speeds. The system is further described by Jones et al. (2005). An important feature of CMOR is that it provides individual error estimates on all measured and derived quantities for each echo. This permits a more detailed examination of data on a case-by-case basis for high speed meteoroids, without the need to appeal to average errors in velocity. In fact, velocity errors measured by an orbital radar can have a strong geometry dependence, so individual error estimation is essential.

CMOR has been in multi-station operation since early 2002, with approximately 2500 meteoroid orbits determined each day. The total orbital dataset size is well over one million orbits. This study covers the time period between May 2002 and September 2004 with all radar downtime taken into account for the final flux calculations.

Each observed echo has an empirically derived estimate for atmospheric deceleration applied to compute an estimated out-of-atmosphere speed (cf. Brown et al., this volume for more details).

Individual meteor masses are estimated based on the mass–speed–electron line density relation developed by Verniani (1973). This mass estimate follows from the minimum electron line density computed in Ceplecha et al. (1998) and described more recently by Cervera et al. (2004). Specifically, each echoes electron line density is estimated taking into account antenna gain. We also note that our masses are lower limits as we implicitly assume the specular point also corresponds to the point of maximum ionisation.

4. Analysis

In order to have high confidence in the validity of any results obtained, a strict set of selection criteria was applied to the dataset. The first step was to select out only those meteoroids which had a heliocentric speed 3σ above the hyperbolic threshold.

The second step involved the direct verification of the fiducial points used in the time-of-flight velocity measurements. This was done by plotting the meteor amplitude as a function of radar pulse number for each meteor echo, and verifying by visual inspection that the fiducial points were determined correctly.

At present, the software regularly employed by CMOR to compute the apparent echo location in the sky may produce incorrect results due to the interferometric algorithm chosen. To account for this, the interferometry was recomputed using an independent, alternate technique, and only those echoes which agreed to the original values to within two degrees were accepted. This is comparable to the expected error in the interferometry (estimated to be on the order of 1°).

Lastly, there is a condition found in the reduction software that forces the meteor trail orientation to always point downward. In the unusual case of the apparent radiant appearing close to the horizon, the associated error in the radiant may cause the meteors to appear to be actually coming from below the horizon. In such cases, the radiant point is placed by the software on the opposite side of the celestial sphere, and in some cases, the orbit may become hyperbolic. This was observed, for example, in connection with the Quadrantid shower in 2003 and 2004, when the peak of that shower occured as the radiant was just rising. To minimise this effect, all echoes having radiants within an angular altitude less than 1σ of the horizon were removed from the analysis.

This strict selection process makes any flux estimates a lower bound, since the actual number of interstellar meteoroids may be much higher. We also repeated the entire analysis procedure accepting all events within a 2σ error bound in heliocentric speed.

5. Results and Discussion

Of the initial 1556384 meteoroids, only 12 remained after all the selection criteria (for the 3σ case) were applied. It is worth noting again that these represent the lower limit of the total number of ISPs we may expect to detect. As well, after the horizon check, the final population shows no potential ISPs with radiant elevations below 6°.

This meteoroid count represents 0.0008% of the intial population. CMOR has a 2500 km^2 average daily integrated collecting area, which is calculated according to the technique described in Brown and Jones (1995). This allows a lower bound on the flux to be estimated at 6×10^{-6} meteoroids/km^2/h, to an effective limiting mass of 10^{-8} kg. When the analysis was redone for the 2σ case, only 40 events remained, which represent 0.003% of the initial population. This provides an estimated flux of 2×10^{-5} meteoroids/km^2/h. Both results are compared to the other observational results in Figure 1, which shows that the flux estimates for CMOR lie very close to a power law extrapolation. However, it is important to note again that the CMOR flux estimates for larger grains represent lower bounds, and the small dust detected by Ulysses/Galileo is of a different dynamical population.

For the 2σ results, the median out-of-atmosphere speed was found to be 56 km/s, and the median heliocentric speed was found to be 68 km/s.

Since the effective limiting error in heliocentric speed for our 2σ results is about 15%, we would expect all meteoroids with a true heliocentric speed greater than 55 km/s to be detected. This corresponds to a minimum pre-solar system encounter speed of 35 km/s. With young stars having pre-solar

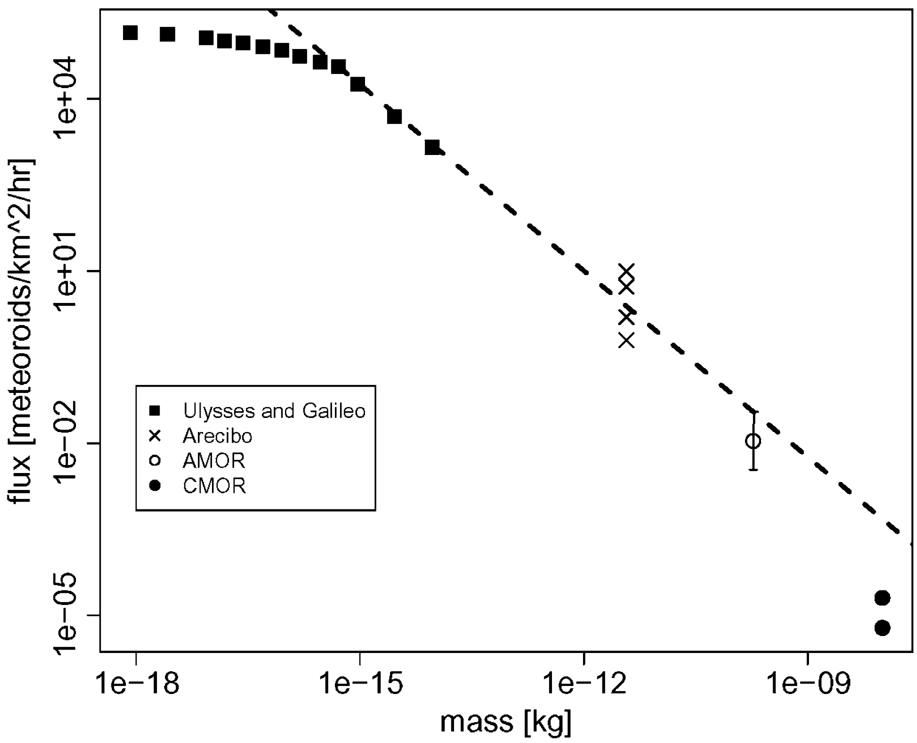

Figure 1. Comparison of flux estimates between various studies. The CMOR values represent lower bounds, with the top one being the 2σ result.

system encounter speeds on the order of 12 km/s (Murray et al., 2004), we are not surprised that there is no significant detectable flux of material in our mass range at these speeds. At ejection speeds larger than 90 km/s, as might be associated with polar outflows from YSOs (Murray et al., 2004), our expected measured atmospheric speed would be greater than 70 km/s, and would be heavily selected against due to initial radius attenuation.

Directional and temporal variations were also considered for the 2σ case. However, there were too few events to provide a statistically meaningful estimate on any potential source regions or outburst times.

6. Conclusions

It was found through a strict selection process of the CMOR orbital data that for an effective limiting mass of 1×10^{-8} kg, a lower limit flux of ISPs equal to 2×10^{-5} meteoroids/km^2/h arrives at the Earth for our 2σ criteria. For our 3σ criteria, the lower limit flux is found to be 6×10^{-6} meteoroids/km^2/h. This larger particle population is of interest for tracing material back to its source region, as these articles are less likely to be perturbed by external forces found in the ISM. Future work will focus on refinements in the data processing, dealing with the declination dependent collecting area instead of an average, and considering a 1σ error bound in the heliocentric speeds.

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