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Micron-Sized Dust Particles Detected in the Outer Solar System by the Voyager 1 and 2 Plasma Wave Instruments

by

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Abstract

During the Voyager 1 and 2 flybys of the outer planets it has been demonstrated that the plasma wave instrument can detect small dust particles striking the spacecraft. In this paper, we examine the Voyager plasma wave data for dust impacts in the interplanetary medium at heliocentric radial distances ranging from 6 to 60 astronomical units (AU). The results show that a small but persistent level of dust impacts exists out to at least 30 to 50 AU. The average number density of these particles is about 2×10^{-8} m^{-3}, and the average mass of the impacting particles is believed to be a few times 10^{-11} g, which corresponds to particle diameters in the micron range. Possible sources of these particles are planets, moons, asteroids, comets, and the interstellar medium. Of these, comets appear to be the most likely source. The number densities are only weakly dependent on ecliptic latitude, which indicates that the particles probably do not originate from planets, moons, or asteroids. Comparisons with interstellar dust fluxes measured in the inner regions of the solar system by the Ulysses spacecraft indicate that the particles are not of interstellar origin.

Introduction

Dust particles in the solar system originate from a variety of sources. Comets shed dust into interplanetary space as they pass through the inner solar system, and meteoroid impacts on the surfaces of planets, moons, and asteroids release dust into Keplerian orbits around the Sun. Dust can also be of interstellar origin, on hyperbolic trajectories that pass through the solar system [Grün et al., 1993]. Light scattered off interplanetary dust can be seen as 'zodiacal light,' a reddened solar spectrum, observable within a few degrees of the Sun shortly after dusk [Abell et al., 1991]. Despite the large number of spacecraft that have been launched to explore the solar system, only a few have been equipped with dust detectors, and none have made dust measurements at heliocentric radial distances beyond 18 astronomical units (AU). In this paper we report the detection of micron-sized dust particles in the outer regions of the solar system, from 6 to 60 AU, using the plasma wave instruments on the Voyagers 1 and 2 spacecraft.

Of the dust detectors that have been flown on interplanetary spacecraft, only four, Pioneer 10 and 11, Ulysses, and Galileo, have provided measurements beyond the orbit of Earth. Pioneer 10 and 11 used an array of 234 pressurized cells as dust detectors [Humes, 1980]. When a high velocity particle penetrates a cell wall the pressure in the cell drops abruptly, indicating an impact. The pressure cells on Pioneer can only be penetrated by relatively large particles, with masses greater than about 10^{-9} to 10^{-8} g, and once a penetration has occurred, no further particles can be detected with that cell. Although Pioneers 10 and 11 provided measurements at large heliocentric radial distances (to 66 AU for Pioneer 10 and 47 AU for Pioneer 11), no cell penetrations have been reported beyond 18 AU. Based on the survival of a thin window Geiger-

Muller tube on Pioneer 11, Van Allen [1994] reported an upper limit of 10^{-6} cm^{-2} s^{-1} sr^{-1} to the flux of particles with masses greater than 10^{-10} g from 1 to 42 AU. The Ulysses and Galileo spacecraft both have very sensitive dust detectors that can detect dust particles as small as 10^{-16} to 10^{-19} g [Grün et al., 1992a, 1992b]. Although these instruments have provided extensive measurements in interplanetary space [Grün et al., 1993, 1996], the orbits of Ulysses and Galileo do not extend beyond the orbit of Jupiter, so the measurements are confined to the inner regions of the solar system, at heliocentric radial distances less than about 5 AU.

Although the Voyager plasma wave instruments were not designed to detect dust impacts, during the Voyager 2 flyby of Saturn's ring plane it was discovered that the plasma wave instrument could detect micron-sized particles striking the spacecraft [Scarf et al., 1982; Gurnett et al., 1983]. When a micron-sized particle strikes the spacecraft, the particle is vaporized by the kinetic energy of the collision, thereby producing a small cloud of plasma that expands rapidly outward from the impact site. As the plasma cloud sweeps over the plasma wave electric antenna, it produces a voltage pulse on the antenna. By counting the number of voltage pulses in a given time, the impact rate can be determined. The particle mass can be estimated from the amplitude of the voltage pulse. Thus, Voyagers 1 and 2, which are now at heliocentric radial distances of 51 and 65 AU, respectively, provide a unique capability to study the distribution of small dust particles in the outer regions of the solar system.

Instrumentation and Method of Detection

The Voyager plasma wave instruments use two cylindrical 10-meter antenna elements to detect the electric field of plasma waves. For a description of the Voyager plasma wave instruments, see Scarf and Gurnett [1977]. In order to provide a dipole response, a differential amplifier is used to measure the voltage difference between the two elements. Signals from the differential amplifier are processed using two types of receivers. The first, a 16-channel spectrum analyzer, provides absolute spectral densities in sixteen frequency channels from 10 Hz to 56.2 kHz. The second, a wideband receiver, provides waveforms of the voltage difference between the antennas over a frequency range from 50 Hz to 12 kHz. Although dust impacts can be identified in both types of data, in this study we only use the wideband waveform data, since these data provide the most reliable method of detecting dust impacts. Normally, the wideband data are sampled in 48-second blocks called frames, which are stored on the spacecraft tape recorder for later transmission to the NASA Deep Space Network. Because the waveform measurements involve very high data rates, 115.2 kbits/s, only a very limited amount of these data can be transmitted to the ground, particularly during the cruise phase where the priority for use of the Deep Space Network is low. Although frame acquisition rates vary, usually an average of only one to two frames per week can be transmitted from each spacecraft.

In the wideband waveform data, an impact appears as an abrupt pulse in the antenna voltage with a rise time of a few microseconds. The initial pulse is followed by an oscillatory recovery waveform that lasts up to several milliseconds. A typical impact signal is shown in Figure 1. Dust impacts can produce either positive or negative pulses, depending on which antenna is closest to the impact site. To determine the impact rate, impacts are first identified by a computer algorithm that calculates the slope of the waveform between two adjacent samples. Two slopes of the same sign exceeding a preset threshold are required before the computer flags an event as an impact. A threshold is introduced to avoid identifying various types of background noise as dust impacts. Occasionally plasma waves trigger the impact detection algorithm. Although the plasma wave activity in the interplanetary medium is relatively infrequent, there are still too many 'false alarms' to allow completely automatic processing. Therefore, each impact waveform identified by the computer must be examined visually to confirm that it is a real impact. This process provides a very reliable method of identifying and counting dust impacts.

Observations

The data used in this study span heliocentric radial distances from 6 to 60 AU. The analysis interval was started at 6 AU in order to avoid contamination by Jupiter at ~5 AU, which is known to be a strong source of interplanetary dust [Grün et al., 1993]. Measurements obtained within about 500 planetary radii from Saturn, Uranus, and Neptune were excluded in order to avoid contamination by dust orbiting these planets. For previous analyses of dust impact measurements near these planets, see Gurnett et al. [1983; 1987; 1991] and Tsintikidis et al. [1994, 1995, 1996]. During the course of this study, a total of 832 frames were examined from Voyager 1, and 1308 frames were examined from Voyager 2. This coverage corresponds to an effective exposure time of 11.09 hours for Voyager 1 and 17.44 hours for Voyager 2. A total of 27 impacts were identified from Voyager 1, and 43 impacts from Voyager 2. The impacts detected have been sorted into 9 AU radial distance bins. The heliocentric radial distance, ecliptic latitude, and number of impacts detected in each bin are summarized in the first three columns of Table 1. The number of impacts in each bin is plotted as a function of heliocentric radial distance in Figure 2. The tick marks at the top of the plot indicate when wideband frames were available. A detailed accounting of the number of wideband frames in each bin is given in the fourth column of Table 1. As can be seen, Voyager 2 detected substantially more impacts than Voyager 1 between 15 and 33 AU. This difference is mainly due to the fact that Voyager 2 had more telemetry coverage than Voyager 1. No impacts were detected by Voyager 1 beyond 51 AU, and no impacts were detected by Voyager 2 beyond 33 AU.

To correct for the nonuniform telemetry coverage, we have computed an average impact rate, R, in each bin by dividing the number of impacts by the total observing time in that bin. The average impact rates are given in the fifth column of Table 1. These impact rates were then used to compute a number density, n, using the equation

$$n = \frac{R}{UA_{s/c}} \quad , \tag{1}$$

where U is the relative velocity between the spacecraft and the impacting particles, and $A_{s/c}$ is the cross-sectional area of the spacecraft. Since the exact speed of the impacting particles is not known, U has been taken to be 20 km/s, which is the approximate heliocentric speed of the spacecraft. The effective cross-sectional area of the spacecraft has been previously estimated by Gurnett et al. [1983] to be approximately $A_{s/c} = 1.66\ m^2$. The number density is shown as a function of heliocentric radial distance in Figure 3. The error bars show the standard deviation. The overall average number density is $2.04\ (\pm 0.39) \times 10^{-8}\ m^{-3}$ for Voyager 1 and $2.06\ (\pm 0.32) \times 10^{-8}\ m^{-3}$ for Voyager 2. As can be seen, the number densities at Voyager 1 remain fairly constant, at a level of a few times $10^{-8}\ m^{-3}$ out to 51 AU, beyond which no impacts were detected. The number density at Voyager 2 has a similar sharp radial cutoff, with no impacts detected beyond 33 AU.

Since one would expect dust from planets, moons, or asteroids to be located near the ecliptic plane, the latitudinal variation of the number density is of considerable interest. As can be seen from Table 1, the ecliptic latitudes of Voyagers 1 and 2 are quite different. After the flyby of Saturn at 9.5 AU, Voyager 1 proceeded northward from the ecliptic plane at an asymptotic ecliptic latitude of about 35°. Voyager 2, on the other hand, remained very close to the ecliptic plane until the flyby of Neptune at 30 AU, after which it proceeded southward from the ecliptic plane at an asymptotic ecliptic latitude of about -34°. Considering these differences in the spacecraft trajectories, the best radial distance range to evaluate the latitudinal variation is from about 15 to 33 AU, when Voyager 1 was well north of the ecliptic plane and Voyager 2 was still near the ecliptic plane. The number densities averaged over this radial distance range are $(2.07 \pm 0.78) \times 10^{-8}$ m^{-3} for Voyager 1 and $(3.60 \pm 0.60) \times 10^{-8}$ m^{-3} for Voyager 2. The difference in these number densities is small, comparable to the statistical uncertainties, indicating that the particles do not originate from planets, moons, or asteroids.

Next we consider the mass of the impacting particles. Of the various quantities that can be obtained from the plasma wave data, the particle mass is one of the most difficult to determine. The threshold mass for detecting a particle impact is given by the simple linear relationship

$$m* = \left(\frac{\beta C_A}{\alpha k}\right) V_{rms} \tag{2}$$

where V_{rms} is the root-mean-square background noise voltage on the antenna, k is an empirically determined mass to charge conversion factor, α is a factor that gives the fraction of the emitted charge collected by the antenna, C_A is the antenna capacitance, and β is the ratio of the minimum detectable voltage to the root-mean-square background noise voltage. For a detailed discussion of the above equation, see Gurnett et al. [1983]. For our purposes, we use the values adopted in the most recent study of dust impacts by Tsintikidis et al. [1994], which are $k = 0.21$ C/g, $\alpha = 0.0055$, $C_A = 90$ pF, and $\beta = 0.51$. For a typical background noise level in the interplanetary medium, we use $V_{rms} = 3 \times 10^{-4}$ V. The threshold mass then works out to be approximately 1.2

× 10^{-11} g. A silicate or water ice particle of this mass would have a diameter of about 1 to 2 μm. Since the mass-to-charge conversion factor could easily vary by up to a factor of ten, depending on the unknown composition and speed of the impacting particle, the threshold mass could vary by up to a factor of ten from the above value.

Discussion

In this paper we have shown that the Voyager 1 and 2 plasma wave instruments detect a small but persistent level of dust impacts in the outer solar system. The average number density of these particles is estimated to be about 2 x 10^{-8} m^{-3}, and the average mass is estimated to be about 10^{-11} g (i.e., in the micron size range). Both the number density and the particle mass depend on the impact velocity, which has been assumed to be the heliocentric velocity of the spacecraft, ~20 k/m. Substantial deviations from this assumed velocity would cause corresponding changes in the estimated number density and particle mass. Possible sources for these particles are planets, moons, asteroids, comets, and the interstellar medium. Of these, we believe that comets are the most likely source. Since the latitudinal gradient is relatively small, it is unlikely that the particles originate from planets, moons, or asteroids. If the particles originated from the interstellar medium, one would expect the number density to be nearly independent of heliocentric radial distance. Instead, both spacecraft show sharp radial cutoffs in the impact rate. No impacts were observed beyond 51 AU for Voyager 1 and beyond 33 AU for Voyager 2. It is unlikely that the absence of impacts at these large radial distances is simply a statistical fluctuation. If the impact rate were to have continued at the average rate observed inside of 51 AU for Voyager 1 and inside of 33 AU for Voyager 2, one would expect to have detected 27 ± 3 impacts in the region beyond 51 AU for Voyager 1 and beyond 33 AU for Voyager 2. The inhomogeneity implied by the total absence of impacts at these large radial distances is inconsistent with an interstellar source. Further evidence against an interstellar source is also provided by observations of interstellar dust with Ulysses [Grün et al., 1993].

Assuming that the particles are arriving at the speed of the interstellar gas, which is about 26 km/s [Witte et al., 1993], the flux detected by Voyagers 1 and 2 (5.2×10^{-4} m^{-2} s^{-1}) would be nearly a factor of ten larger than the flux of interstellar dust (8×10^{-5} m^{-2} s^{-1}) reported by Grün et al. [1993]. Thus, it is unlikely that the particles being detected by Voyager are of interstellar origin. At present, we have no specific explanation for the apparent radial cutoff in the number density at 51 AU for Voyager 1 and at 33 AU for Voyager 2. However, since the distribution of cometary orbits is likely to be highly irregular, the existence of such inhomogeneities is not inconsistent with a cometary source.

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Table 1. Summary of impacts detected and available data coverage

Radial Distance (AU)	Ecliptic Latitude (degrees)	Number of Impacts Detected	Number of 48-s Frames Analyzed	R, impact rate, s^{-1}
		Voyager 1		
6 → 15	1 → 22	5	186	5.6×10^{-4}
15 → 24	22 → 29	5	120	8.7×10^{-4}
24 → 33	29 → 32	2	92	4.5×10^{-4}
33 → 42	32 → 33	8	106	15.7×10^{-4}
42 → 51	33 → 34	7	161	9.0×10^{-4}
51 → 60	34 → 34	0	167	0.0×10^{-4}
		Voyager 2		
6 → 15	1 → 1	7	272	5.3×10^{-4}
15 → 24	1 → 0	19	306	12.9×10^{-4}
24 → 33	0 → -1	17	308	11.5×10^{-4}
33 → 42	-4 → -14	0	329	0.0×10^{-4}
42 → 51	-14 → -21	0	93	0.0×10^{-4}

Figure Captions

Figure 1. A typical dust impact signal in the wideband plasma wave data. The very abrupt jump in the antenna voltage (marked with an arrow) indicates a dust impact. The subsequent oscillatory decay is due to saturation effects in the receiver.

Figure 2. Plots showing the number of dust impacts detected by Voyager 1 and Voyager 2 as a function of heliocentric radial distance. The tick marks at the top of each plot indicate the number of wideband waveform frames available. Note the complete absence of impacts beyond 51 AU for Voyager 1 and beyond 33 AU for Voyager 2, even though adequate data are available in these regions.

Figure 3. Plots showing the number density of dust particles as a function of heliocentric radial distance, assuming an impact velocity of 20 km/s. Both spacecraft encountered number densities on the order of a few times 10^{-8} m^{-3}. Note the sharp radial cutoff in the number density at 51 AU for Voyager 1 and at 33 AU for Voyager 2.

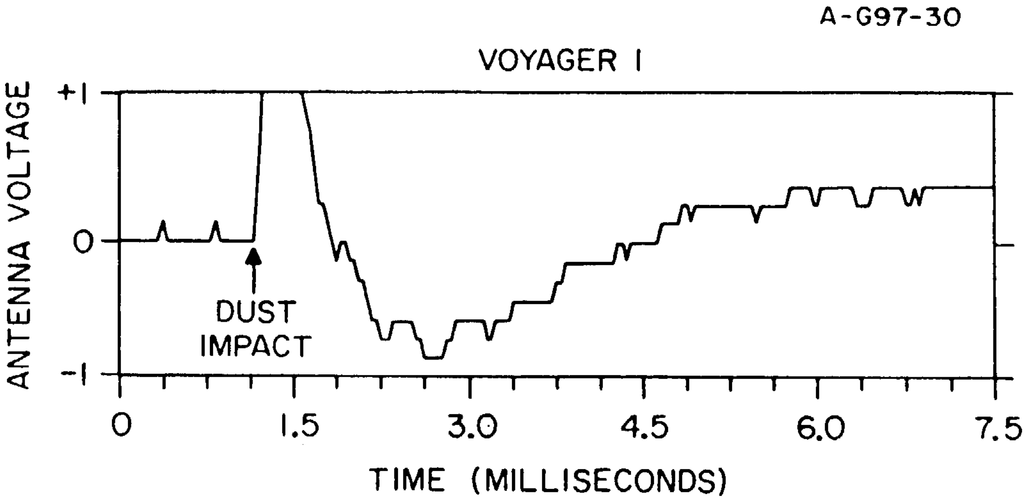
A-G97-30
VOYAGER I
ANTENNA VOLTAGE
+1
0
-1
DUST
IMPACT
0
1.5
3.0
4.5
6.0
7.5
TIME (MILLISECONDS)

Figure 1

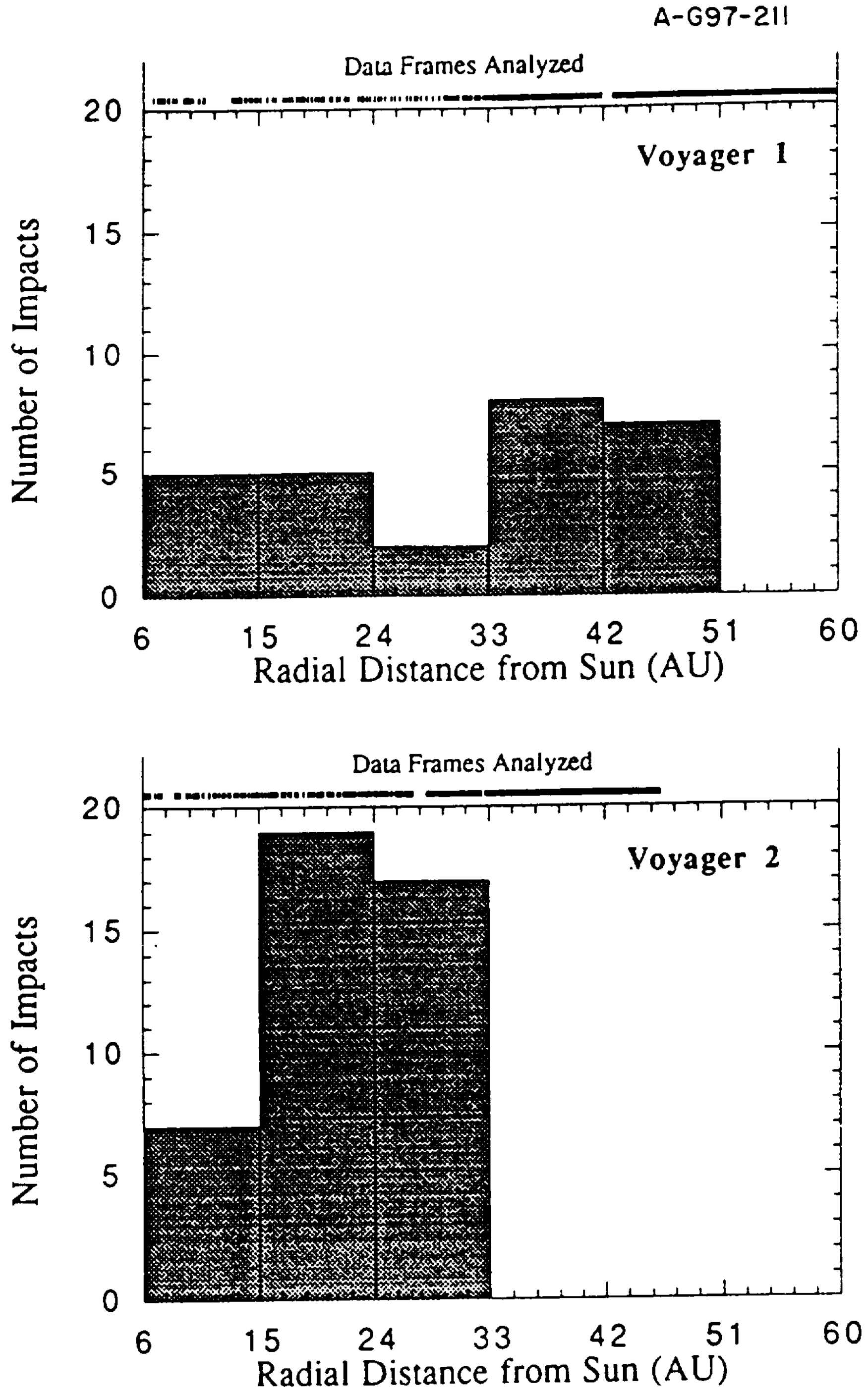
A-G97-211
Data Frames Analyzed
Voyager 1
Number of Impacts
0
5
10
15
20
6
15
24
33
42
51
60
Radial Distance from Sun (AU)
Data Frames Analyzed
Voyager 2
Number of Impacts
0
5
10
15
20
6
15
24
33
42
51
60
Radial Distance from Sun (AU)

Figure 2

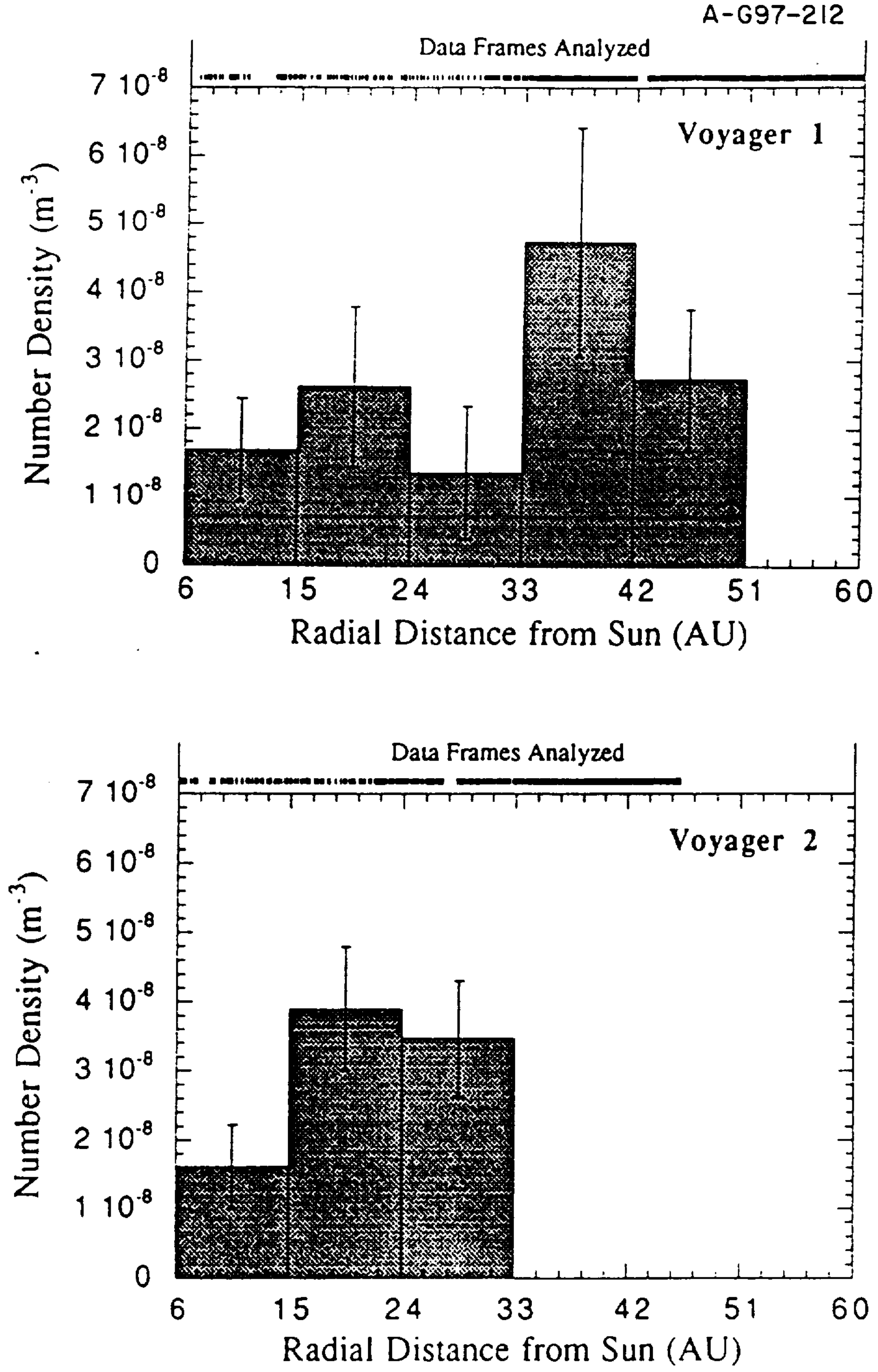
A-G97-212
Data Frames Analyzed
Voyager 1
Number Density (m^{-3})
7 10^{-8}
6 10^{-8}
5 10^{-8}
4 10^{-8}
3 10^{-8}
2 10^{-8}
1 10^{-8}
0
6
15
24
33
42
51
60
Radial Distance from Sun (AU)
Data Frames Analyzed
Voyager 2
Number Density (m^{-3})
7 10^{-8}
6 10^{-8}
5 10^{-8}
4 10^{-8}
3 10^{-8}
2 10^{-8}
1 10^{-8}
0
6
15
24
33
42
51
60
Radial Distance from Sun (AU)

Figure 3