IN-92
60415-CR
P-13

RECEIVED
MAR 24 1987
A. J. LAZARUS

The Pick-Up of Cometary Protons by the Solar Wind

M. Neugebauer[1], [redacted], K. Altwegg[3], H. Balsiger[3], B. E. Goldstein[1], R. Goldstein[1], F. M. Neubauer[4], H. Rosenbauer[5], R. Schwenn[5], E. G. Shelley[6], E. Ungstrup[7]

JJ574458
MJ700802
BN790295
CT792031
ML789520
1535551
DF551649

1) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 USA
2) Massachusetts Institute of Technology, Cambridge, MA, USA
3) Physikalisches Institut, University of Bern, Bern, Switzerland
4) Institut für Geophysik und Meteorologie der Universität Köln, Köln, Federal Republic of Germany
5) Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Federal Republic of Germany
6) Lockheed Palo Alto Research Laboratory, Palo Alto, CA, USA
7) Danish Space Research Institute, Lyngby, Denmark

SUMMARY

The HERS detector of the Ion Mass Spectrometer on the Giotto spacecraft measured the 3-dimensional distribution of picked-up cometary protons over a distance of ~8 million km upstream of the bow shock of Comet Halley. The protons were observed to be elastically scattered out of their original cycloidal trajectories such that they were nonuniformly distributed over a spherical shell in velocity space. The shell radius (relative to its expected radius) and thickness increased as the bow shock was approached. Downstream of the shock, the cometary protons could not be distinguished from the heated solar wind protons.

Keywords: Comets, Plasmas, Interplanetary medium

(NASA-CR-180212) THE PICK-UP OF COMETARY PROTONS BY THE SOLAR WIND (Jet Propulsion Lab.) 13 p CSCL 03B

N87-19342

Unclas
G3/92 43657

1. INTRODUCTION

The first part of a comet sensed by the solar wind is its extensive corona of atomic hydrogen. The comet-solar wind interaction begins when these H atoms are ionized, either by photoionization or by charge-exchange collisions with the solar wind, and the newly ionized protons respond to the electric and magnetic fields in the solar wind. This paper briefy summarizes some of the principal features of this initial interaction and pickup of cometary protons.

2. INSTRUMENTATION

The data presented here were obtained by the High Energy Range Spectrometer (HERS) of the Giotto Ion Mass Spectrometer (IMS) experiment. The instrument design and performance have been described by Balsiger et al. (1986a,b). With this instrument, it was possible to study separately the velocity distributions of each ion species (i.e. each narrow range of mass/charge ratio, M/Q). Only proton data are considered here.

During the period of interest, HERS mapped the distribution of protons every fourth spacecraft spin (i.e., 4 s out of every 16 s). A separate channel electron multiplier detector (CEM) counted the flux of protons in each of four elevation angle bins, which viewed the protons incident at angles with respect to the spacecraft spin direction of 15 to 30° (CEM D), 30 to 45° (CEM C), 45 to 60° (CEM B), and 60 to ~70° (CEM A). The spacecraft spin axis was closely aligned with the relative velocity vector between the spacecraft and the comet and was pointed toward the comet. During each four-second spin, the proton counts were sorted into 31 azimuth bins (11.25° each) and 64 quasi-logarithmically spaced energy bins, ranging from 10 to 4024 eV. The total field of view for protons was thus 349° x ~55°.

3. PRELIMINARY RESULTS

The method used to identify protons of cometary origin is illustrated in Figure 1. Shown as small plots A, B, C, and D are polar plots of contours in velocity space of the proton phase-space density, f(v), observed with the four CEM detectors A, B, C, and D, respectively, during the interval 0803 to 0908 spacecraft event time (SCET), March 13. Each plot represents the distribution on a conical surface; the horizontal axis corresponds to flow in the plane defined by the spacecraft spin vector and the direction to the Sun while positive vertical values correspond to flow with a northward component. Figure 1A shows data from CEM A, whose field of view was furthest from the spin axis and included the solar wind. The peak of the solar-wind distribution is indicated by an "x" in the center of the roughly circular contours. At this time, the solar wind speed was 397 km/s relative to the spacecraft. The distortion of the contours at low energy is due to inaccuracies in the preliminary algorithms used for processing the low-energy proton data. Three contour levels represent a one-decade change in phase-space density. With increasing displacement from the "x" at the peak of the solar-wind distribution in Figure 1A, the phase-space density decreased monotonically across 16 contour levels (>5 orders of magnitude); the outer four contour intervals have been shaded, with a darker shade representing a higher value of f(v). Two still lower density levels have been left unshaded in Figure 1A. Even further outward from the "x", at the bottom of the frame (corresponding to flow with a southward component), the phase-space density climbed again, through four contour levels, as again indicated by shading. This outer arc is due to the pickup protons. Because the phase-space density of the pickup protons was about four orders of magnitude less than that at the peak of the solar-wind proton distribution, it is necessary to sum the data over many spins; 237 spins of proton data were used to generate Figure 1. During the time that the data in Figure 1 were obtained, the direction of the interplanetary magnetic field remained relatively steady with solar-ecliptic latitude and longitude angles of +26 and 13°, respectively. The expected location in velocity space of picked-up cometary protons can be calculated as follows: The photo-dissociation of cometary water leads to H atoms with speeds, a, of 8 and 20 km/s (Keller, 1976). Since both these values are considerably less than the 43.8 km/s heliocentric speed of the comet, which was in turn considerably less than the solar-wind speed, the velocity of the picked-up protons is relatively insensitive to the precise value of the magnitude of a. For the calculations which follow, it is assumed that a = 11 km/s, in keeping with the results of analysis of Lyman-alpha observations of comet Halley by Suisei (Kaneda et al., 1986).

Since the velocity of the spacecraft was directed towards the comet and the relative speed between the two was 68.4 km/s, the neutrals appeared to come from the direction of the comet with velocity v_n = (68.4 + a) km/s. In a reference frame moving with the solar wind, the velocity of a newly created proton would be $\vec{v}_r^{\,*} = \vec{v}_n - \vec{v}_{sw}$, where $\vec{v}_n$ and $\vec{v}_{sw}$ are the velocities of the neutrals and the solar wind, respectively, in the spacecraft frame. Resolution of the velocity $\vec{v}_r^{\,*}$ into components perpendicular and parallel to the interplanetary magnetic field allows calculation of the protons' helical motion (a ring in velocity space in the solar-wind reference frame). The trace of the ring of freshly ionized hydrogen through the instrument field of view can be calculated. The intersections of this ring with the fields of view of the four CEMs are shown by crosshatching in Figure 1.

It is clear from Figure 1 that the location of the pickup protons in velocity space includes but extends beyond the (cross-hatched) locations expected for newly created ions spiralling around the local magnetic field. There is evidence that the pickup protons have been scattered in pitch angle so that they occupy a large part of a spherical shell with radius v_r^*, centered at the solar-wind velocity. The scattering was not sufficiently intense, however, to fill the shell uniformly. The curves showing the intersections of this shell with the conical surfaces mapped out by the four CEMs are also indicated in Fig. 1. The population of picked-up protons is spread out from the expected ring location along these curves.

The band of pickup protons is broader for CEM-D than for the other detectors because the shell is nearly tangent to the field of view of this sensor.

A similar set of four diagrams is given in Figure 1 of Neugebauer et al. (1986) for the time interval 1436-1552 SCET, March 13, when the field direction was not quite so steady as in the interval shown in Figure 1 above. In that case, the shells were nearly completely filled.

At this distance of nearly 4 million km from the comet, the thickness of the shell was roughly consistent with the energy resolution of the instrument. There is no strong evidence for energy diffusion or heating of the protons in the shell; this question will be examined in greater detail in future work. In summary, until the spacecraft was quite close to the shock, the picked-up protons were nonuniformly distributed over a spherical shell in velocity space, with the shell center and radius determined by the velocities of the solar wind and the comet. This result is consistent with the two-dimensional measurements made by Suisei (Terasawa et al., 1986).

Better statistics on the radius (in velocity space) and the thickness of the shell of pickup protons can be obtained by calculating the distribution of the magnitudes of the vectors $\Delta\vec{v} = \vec{v} - \vec{v}_{SW}$. Figure 2 shows the average f(v) plotted versus $|\Delta\vec{v}|/v_r^*$ for several intervals when the solar-wind velocity was relatively steady. These curves were obtained by sorting the proton counts obtained in each energy-azimuth-elevation bin into bins of $|\Delta\vec{v}|$, each bin being 20-km/sec wide, then averaging the contents of each $|\Delta\vec{v}|$ bin, and finally dividing $|\Delta\vec{v}|$ by v_r^* before plotting. In the ideal case of a perfectly calibrated instrument with very narrow energy and angular resolution, if all the newly ionized protons had been picked up at the same solar wind speed and had no energy changes thereafter, this plot would show a sharp spike at $|\Delta\vec{v}|/v_r^* = 1$, superimposed on the flank of the solar-wind distribution function.

Each curve in Figure 2 is labelled according to the times (in SCET) of the first and last data included. Upstream of the shock crossing at ~1930 SCET, the data show rather broad peaks near $|\Delta\vec{v}|/v_r^* = 1.0$, with the positions and the widths of the peaks increasing as the comet was approached. Far upstream of the shock, the radius of the shell appeared to be somewhat less than expected. It is possible that this effect is not real, but that it is due to a combination of instrumental factors which are currently under investigation. The widths of the peaks in the first three curves in Figure 2 are not significantly broader than the widths expected from instrumental smear; future modeling efforts will allow quantitative comparisons of these distributions to those expected for pickup shells of infinitesimal thickness. There is no question, however, about the reality of the increasing radius (relative to the expected value of v_r^*) and of the increasing thickness of the shell as the shock is approached.

These changes can be ascribed to a combination of effects. First, the instrument always detected cometary protons ionized over a range of distances upstream of the spacecraft. The "older" protons, which were picked up further upstream where the solar-wind speed was presumably higher, should be on a larger-radius shell than should the "young" protons picked up locally. In addition, the protons in the shell would be adiabatically heated as the solar wind was decelerated and compressed (Ip and Axford, 1986). Although there is a mixture of ages of pickup protons at all distances from the shock, the effect becomes much more pronounced close to the shock where the pickup of heavier ions, such as C^+ and O^+, increases the rates of mass loading and slowing of the solar wind. Separation of the effect of superposition of shells of protons with different ages from the effect of adiabatic acceleration will be very difficult to model because the Giotto spacecraft approached the comet from a direction nearly perpendicular to the solar-wind streamlines instead of along a single streamline. Although the solar-wind velocity did, on the average, decrease as the bow shock was approached, this decrease was not smooth. It can be seen from Figure 1 of Johnstone et al. (1986) that in this upstream region, the spacecraft crossed many discontinuities separating plasmas of different speeds.

Two additional effects which could broaden the shell symmetrically -- both inward and outward from its nominal position -- are energy diffusion and an increased level of variation in $\vec{v}_{SW}$ associated with an increased amplitude of turbulence close to the bow shock. Neither of these effects were apparently very important outside the bow shock.

It is apparent from the bottom curve in Figure 2 that inside the shock, the shell of pickup protons could no longer be distinguished from heated solar-wind protons. At this time, protons were detected in all energy channels of the instrument, which included velocities as high as ~850 km/s. The presence of protons with energies ~16 times the local bulk flow energy is indirect evidence for the continuing presence of protons picked up at higher speeds and of additional energization processes as well.

Pickup protons were first detected at ~1700 UT on March 12, the day before encounter when the spacecraft was nearly 8 million km from the comet. The dependence of the number of picked-up protons on distance from the comet can be crudely estimated from Figure 3, which shows the integral under the pickup-proton peaks (in curves like those shown in Figure 2) plotted versus distance from the comet nucleus. Two effects are evident in Figure 3. First, there is a general dropoff associated with the expected decrease in the number of H atoms with distance from the comet. A least-squares fit to the data produces an average dropoff proportional to $r^{-1.75}$. Second, there are very large fluctuations about the average dropoff rate caused by (a) spatial inhomogeneities in atomic H arising from time variations in cometary activity, (b) perhaps some variation in the rate of charge exchange collisions between H atoms and the temporally and spatially varying solar wind, and (c) variations in the direction of the interplanetary magnetic field, which causes changes in how the cycloidal motion of picked-up protons cuts through the field of view of the instrument. Further work on untangling these various effects and on determining the rate of pitch-angle and energy scattering is in progress.

4. ACKNOWLEDGMENTS

The research described in this paper was carried out, in part, by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the US National Aeronautics and Space Administration. The work at MIT was partially supported by NASA grant NGL 22-009-015.

5. REFERENCES

Balsiger, H., Altwegg, K., Bühler, F., Fischer, J., Geiss, J., Meier, A., Rettenmund, U., Rosenbauer, H., Schwenn, R., Benson, J., Hemmerich, P., Sager, K., Kulzer, G., Neugebauer, M., Goldstein, B.E., Goldstein, R., Shelley, E.G., Sanders, T., Simpson, D., Lazarus, A.J., Young, D.T.:1986a, in The Giotto Mission -- Its Scientific Investigations, ESA SP-1077, ed R. Reinhard and B. Battrick, p.129

Balsiger, H., Altwegg, K., Bühler, F., Geiss, J., Ghielmetti, A.G., Goldstein, B.E., Goldstein, R., Huntress, W.T., Ip, W.-H., Lazarus, A.J., Meier, A., Neugebauer, M., Rettenmund, U., Rosenbauer, H., Schwenn, R., Sharp, R.D., Shelley, E.G., Ungstrup, E., Young, D.T.:1986b, Nature 321, 330

Ip, W.-H., Axford, W.I.:1986, Planet. Space Sci. 34, 1061

Johnstone, A. D., Coates, A.J., Heath, L., Thomsen, M.F., Wilken, B., Jockers, K., Formisano, V., Amata, E., Winningham, J.D., Borg, H., Bryant, D.:1986, in Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet, ESA SP-250, ed B. Battrick, E. J. Rolfe, and R. Reinhard, p.25

Kaneda, E., Hirao, K., Shimizu, M., Ashihara, O.,:1986, Geophys. Res. Lett. 13, 833

Keller, H.U.:1976, Space Sci. Rev. 18, 641

Neugebauer, M., Lazarus, A.J., Altwegg, K., Balsiger, H., Goldstein, B.E., Goldstein, R., Neubauer, F.M., Rosenbauer, H., Schwenn, R., Shelley, E.G., Ungstrup, E.:1986, in Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet, ESA SP-250, ed B. Battrick, E. J. Rolfe and R. Reinhard, p. 19

Terasawa, T., Mukai, T., Miyake, W., Kitayama, M., Hirao, L.:1986, Geophys. Res. Lett. 13, 837

FIGURE CAPTIONS

Fig. 1. Phase space density contours of CEMs A-D for the period 0803-0908 UT, March 13, 1986.

Fig. 2. Average phase space density as a function of displacement in velocity space from the solar-wind bulk speed; see text for the definition of terms. The short, horizontal lines on each spectrum denote equal values of $\langle f(v) \rangle$.

Fig. 3. Average phase space density of the part of the shell of pickup protons within the field of view of the HERS instrument versus distance from the comet nucleus.

ORIGINAL PAGE IS
OF POOR QUALITY

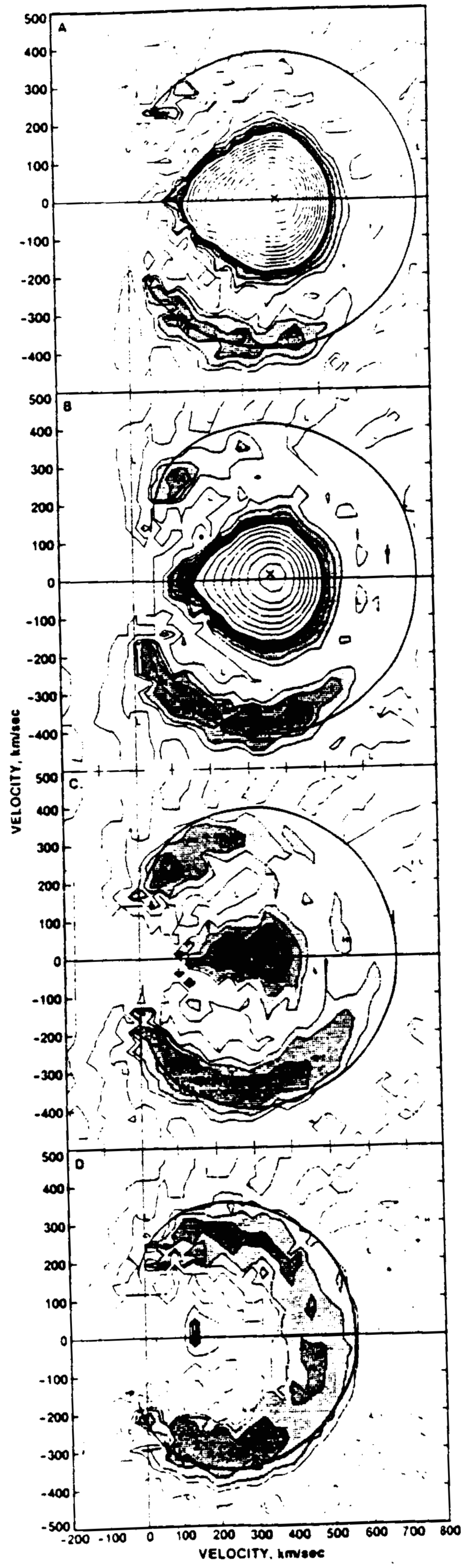

FIGURE 1

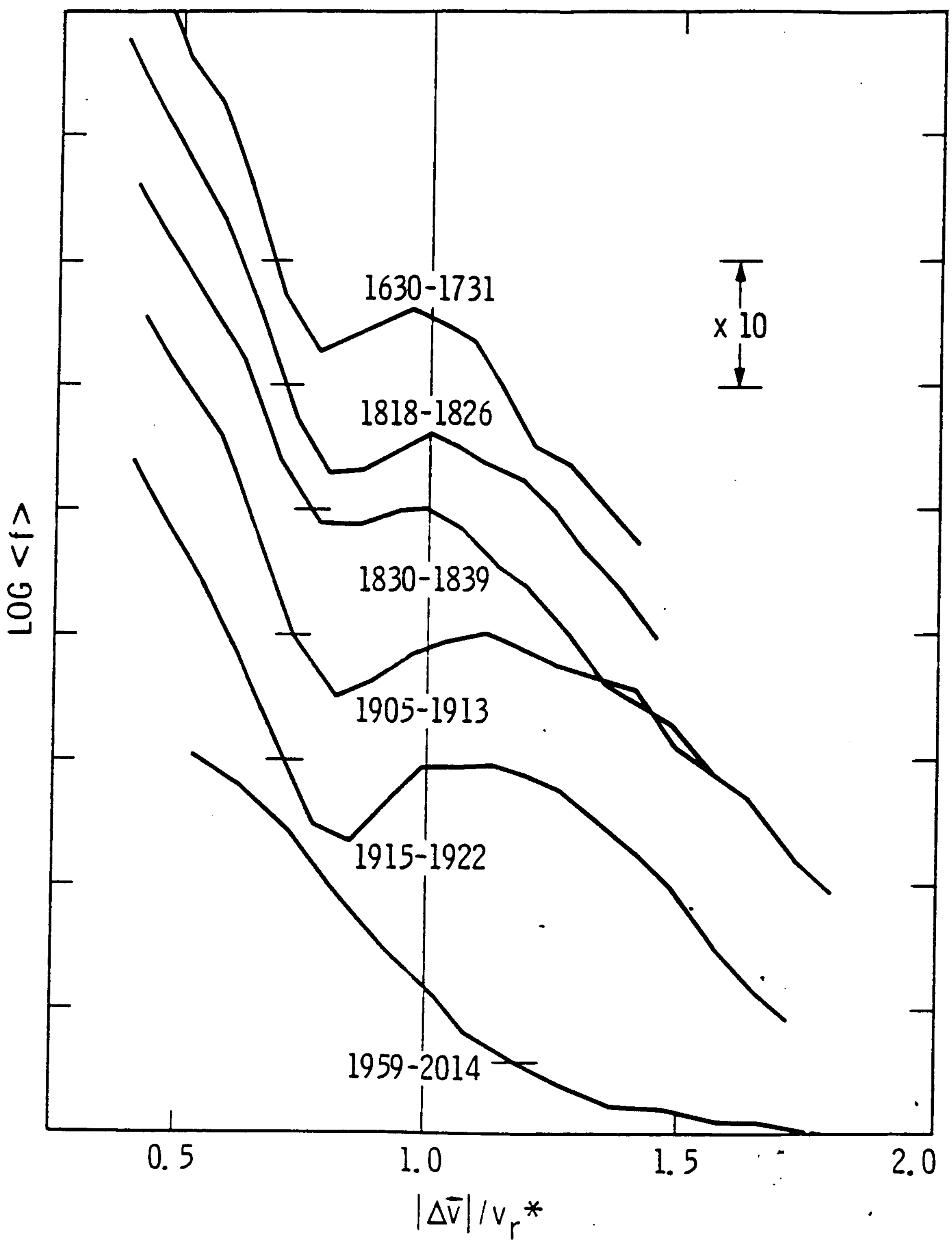
1630-1731
1818-1826
1830-1839
1905-1913
1915-1922
1959-2014
x 10
LOG <f>
0.5
1.0
1.5
2.0
|Δv̄|/v_r*

FIGURE 2

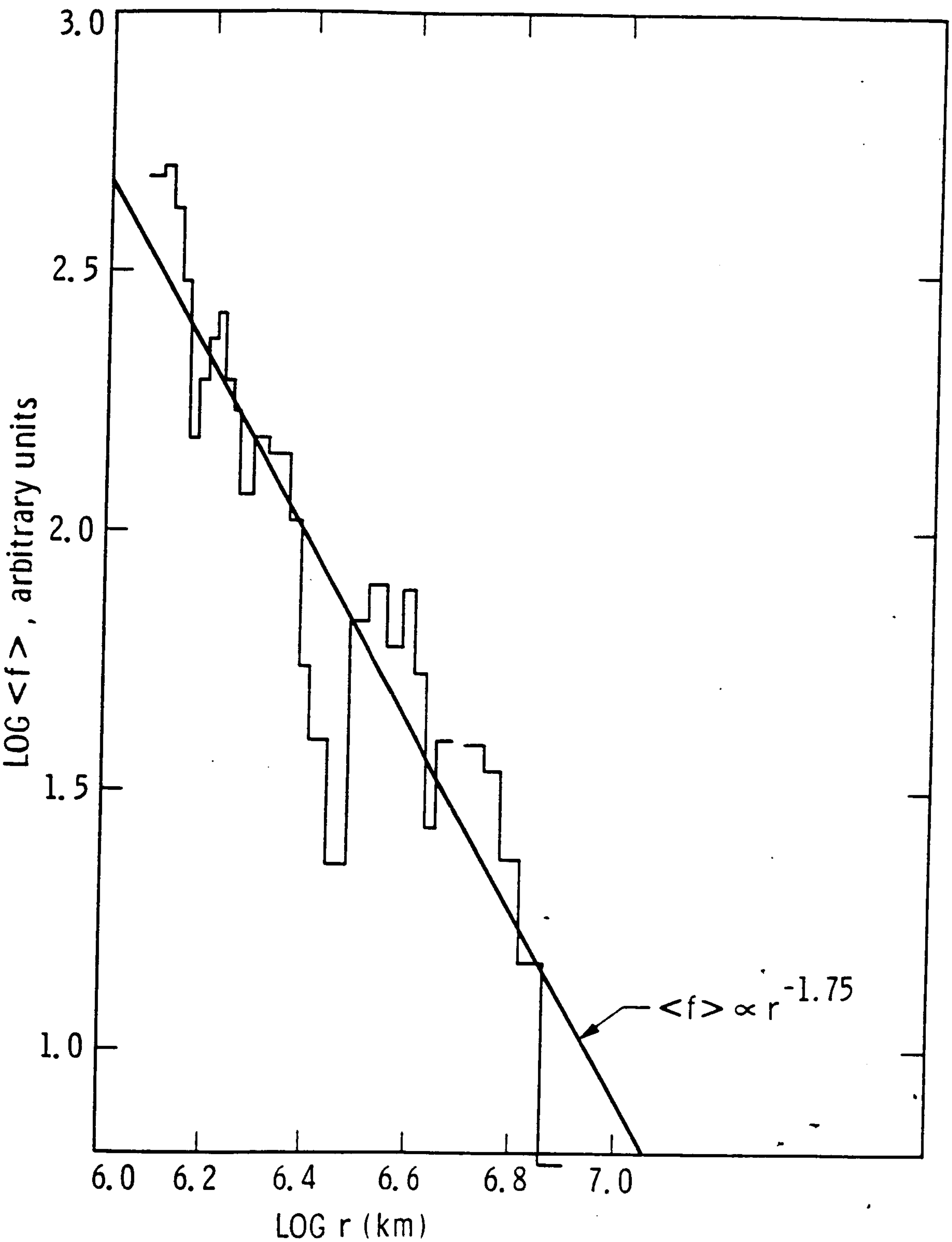
3.0
2.5
2.0
1.5
1.0
LOG <f> , arbitrary units
<f> ∝ r^-1.75
6.0
6.2
6.4
6.6
6.8
7.0
LOG r (km)

FIGURE 3