1992ApJ...388..190W

THE ASTROPHYSICAL JOURNAL, 388:190–195, 1992 March 20

VELOCITY STREAMING OF *IRAS* MAIN-SEQUENCE DISK STARS AND THE EPISODIC ENHANCEMENT OF PARTICULATE DISKS BY INTERSTELLAR CLOUDS

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Received 1991 March 21; accepted 1991 September 30

ABSTRACT

We have discovered evidence of velocity streaming in a set of nearby main-sequence A-type *IRAS* disk stars. This conservatively chosen set of the five most significant particulate-disk stars consists of β Pic, α Lyr, α Psa, β Leo, and ζ Lep. Monte Carlo simulations were used to compare the velocity dispersion of this set to the dispersions of sets chosen at random from the remaining 17 main-sequence A stars listed in the Gliese catalog (<22 pc). It was found that dispersion velocities less than those of the particulate-disk star set occurred by chance in only 2% of the cases.

Small dispersion velocities are normally indicative of streaming clusters or young field stars. However, the velocity dispersion of the set of particulate-disk stars is inconsistent with either interpretation. These stars did not originate in the local association but, within velocity uncertainties, their centroid trajectory did pass through a major cloud in the local association which today lies in the general direction of Centaurus. We suggest that the streaming is a selection artifact of a model in which observable particulate disks are produced or greatly enhanced by episodic passages through interstellar clouds. The disk area enhancement is due to multiple impact fragmentation of ambient circumstellar grains by interstellar grains.

Subject headings: circumstellar matter — infrared: stars — ISM: general — stars: kinematics

1. INTRODUCTION

Half of the 22 A stars lying within 22 pc of the Sun have been found to exhibit some level of nonphotospheric IR emission in one or more *IRAS* bands (Aumann 1985, 1988; Backman & Gillett 1987, hereafter BG; Backman & Paresce 1991). The source of this Vega-like emission is generally believed to be orbiting circumstellar grains (Aumann et al. 1984). Since it is expected theoretically that collisions will result in the grain orbits relaxing to a flattened configuration, and to distinguish these stars from Galactic disk stars, we will refer to these Vega-like main-sequence stars as particulate-disk stars.

While investigating the effects of collisions between interstellar dust clouds and circumstellar disks, we discovered that our set of the five most significant disks had an unusually small velocity dispersion. The dispersion was small when compared to the complete set of nearby stars in the Gliese catalog and even smaller when compared to that of a large number of old A stars within several hundred parsecs. A small velocity dispersion of a group of stars is normally interpreted in terms of streaming siblings with a common cloud origin or in terms of approximately randomly moving young field stars. In this case, however, we shall argue that the observed velocity dispersion is too large for the former and too small for the latter interpretation. We suggest instead that it is due to a selection bias of a model in which the particulate-disk area is collisionally enhanced by passage through interstellar clouds.

In § 2 we discuss our particulate-disk star selection criteria and then evaluate the statistical significance of the observed small velocity dispersion. The implications of the small velocity dispersion are considered in § 3. In § 4 we discuss the multiple impact fragmentation model and in § 5 we present evidence for the recent passage of the particulate-disk set through an interstellar cloud. Conclusions and additional tests of the model are discussed in § 6. The Appendix contains the multiple impact fragmentation analysis which illustrates how disk area can be increased by passage through a cloud.

2. STATISTICAL SIGNIFICANCE OF SMALL VELOCITY DISPERSION

Since all single stars are likely to have circumstellar particulate disks at some instrument threshold, their separation into particulate-disk stars and non–particulate-disk stars is necessarily arbitrary. The *IRAS* band signal-to-noise uncertainties vary by up to an order of magnitude (BG). This background fluctuation is especially troublesome for stars in the line of sight of cirrus clouds. Because selection criteria varied, there is incomplete overlap in the nearby particulate-disk stars listed by BG and Aumann (1988). For these reasons caution was needed in selecting a set of disk stars which could be used to investigate the set's kinematical properties. The desired set would contain only those stars for which there was general agreement that a significant particulate disk existed.

In order to have a uniform sample and to minimize observational bias we considered only the complete set of nearby A dwarf stars listed in the Gliese catalog (<22 pc). A similar restriction to A dwarfs has also been adopted by other authors (Lissauer & Griffith 1989). None of the later spectral types survived the following selection criteria in any case, with the single exception of ϵ Eri. Of this complete set of 22 A stars, a total of 11 have been reported to have IR excesses at some statistical level. Of these 11 stars we selected only those which were detected in two or more *IRAS* bands in *both* the BG and Aumann (1988) searches. These criteria reduced the particulate-disk set to five stars. They are the original three prototypes: α Lyr, α Psa, and β Pic plus ζ Lep and β Leo. This approach naturally has the disadvantage of small number statistics, but we believe that this is outweighed by the added security that none of our disk stars are spurious.

TABLE 1

VELOCITIES OF NEARBY A STARS

Gliese Number	Star	U	V	W
217.1.........	ζ Lep	−14	−11	−9
219.0.........	β Pic	−11	−16	−9
448.0.........	β Leo	−24	−19	−10
721.0.........	α Lyr	−17	−6	−8
881.0.........	α Psa	−5	−7	−10
20.0.........	κ Phe	−6	−4	−12
80.0.........	β Ari	−2	−11	−3
121.0.........	τ^3 Eri	16	9	1
244.0.........	α Cma	15	0	−11
248.0.........	α Pic	−22	−20	−9
278.0.........	α Gem	−7	−4	−11
321.3.........	δ Vel	7	−1	−3
331.0.........	ι Uma	−32	−14	−15
333.3.........	α Vol	8	−2	−7
459.0.........	δ Uma	12	0	−9
508.1.........	ι Cen	−24	−22	−4
564.1.........	HD 130841	−11	−7	−6
580.1.........	β Cir	−4	−19	−8
656.1.........	η Oph	−3	9	2
673.1.........	HD 157792	−36	−11	−10
768.0.........	α Aql	−29	−10	−2
826.0.........	α Cep	−9	−11	−7

NOTES.—The heliocentric velocities in km s^{-1} of the main-sequence A stars within 22 pc of the Sun. The velocities of the set of five particulate-disk stars discussed in the text are listed at the top followed in order of Gliese number by the remaining 17 control stars.

Table 1 tabulates the heliocentric velocities (U, V, W) of the 22 A stars in the Gliese catalog. Our conservatively chosen particulate-disk star set is listed at the top, followed in Gliese number order by the remaining control stars. Inspection of the table shows that the particulate-disk stars apparently have a significantly smaller velocity dispersion than a typical set of five stars chosen from the controls. The components of the dispersion velocity (σ_U, σ_V, σ_W) are determined from

$$\sigma_U = [\Sigma(U_i - \bar{U})^2/N]^{1/2} \tag{1}$$

and the corresponding formulae for the σ_V and σ_W components. The particulate-disk star components are found to be (7, 6, 1) in km s^{-1}. The expected dispersion velocity of a large set of young ($<0.5 \times 10^8$ yr) A stars is (10, 10, 8) and that expected for a large set of old ($0.8–1.0 \times 10^9$ yr) A stars is (18, 13, 8) (Palous 1986). The dispersion velocity of the 17 local controls is (13, 8, 4) and that of the 11 local A stars for which no excess has been reported by BG or Aumann (1988) is (15, 8, 5).

The statistical significance of the small velocity dispersion of the particulate-disk stars was evaluated using Monte Carlo simulations. Sets of five stars were chosen at random from the 17 control stars listed in Table 1. In each case the control star dispersion velocity ellipsoid was calculated and compared to that of the particulate-disk star set. After 1000 comparisons the particulate-disk star dispersion velocity volume, $(4\pi/3)\sigma_U \sigma_V \sigma_W$, was found to be smaller than the control star measure in 98% of the cases.

3. IMPLICATIONS OF SMALL VELOCITY DISPERSIONS

A localized group of stars having a small velocity dispersion will also have a small spatial dispersion when projected backward or forward in time. All stars within 22 pc of the Sun have relatively little spatial dispersion today, but the spatial dispersion will diverge rapidly in the past and future if the stars are moving randomly. The spatial dispersion of the set of particulate-disk stars does not diverge as rapidly as the controls when projected into the past. We have integrated the trajectories of the particulate-disk stars and 1000 sets of five randomly chosen control stars in the local standard of rest (LSR). Assuming linear motion, we calculate the spatial dispersion volume $(4\pi/3)\ \sigma_X \sigma_Y \sigma_Z$ as a function of time during the past 10 Myr. The results for the particulate-disk set and the mean of control sets are shown in Figure 1. As expected, there is no significant difference between the two groups at present. However, asymptotically the particulate-disk stars dispersion volume is an order of magnitude smaller than that of the control stars. The dip in the particulate-disk star volume at 1 Myr is due to small number statistics and is of no physical significance.

The best measure of the statistical significance of the small spatial dispersion of the particulate-disk stars is illustrated in Figure 2 where we have plotted spatial (and speed) probability versus time. At each time the dispersion volume of the set of five particulate-disk stars was compared to 1000 sets of five randomly chosen control stars. The probability at that time is the fraction of cases for which the particulate-disk star set had a smaller dispersion volume than the control star set. The figure again illustrates that the present dispersion volume of particulate-disk stars is not unusual, but because of their small dispersion velocity they do not disperse as rapidly as the controls in the past. As expected, the dispersion volume probability asymptotically approaches the constant dispersion velocity probability of 98%.

Conventionally, groups of stars with small dispersion velocities have been explained in one of two ways. Streaming superclusters (Eggen 1989) are groups of stars which originated in the same cloud and consequently have very small dispersion velocities (≈ 1 km s^{-1}). Young, nonstreaming field stars originate in different clouds and are therefore moving approximately randomly. Initially the field stars have a velocity dispersion that reflects that of their parent clouds

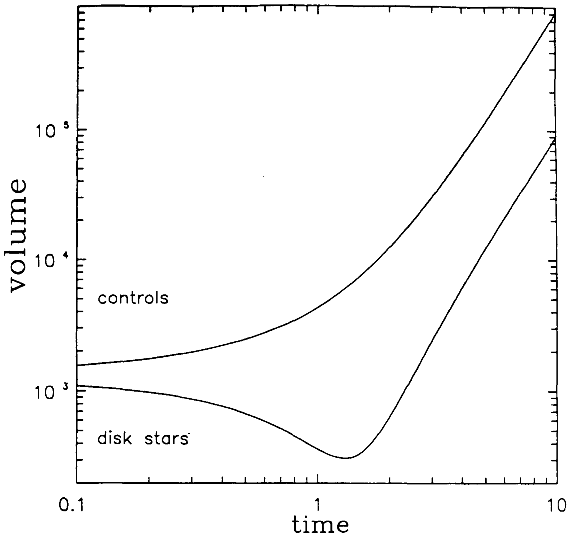

FIG. 1.—The dispersion volume in pc^3 as a function of past time in Myr for the particulate-disk star and control sets.

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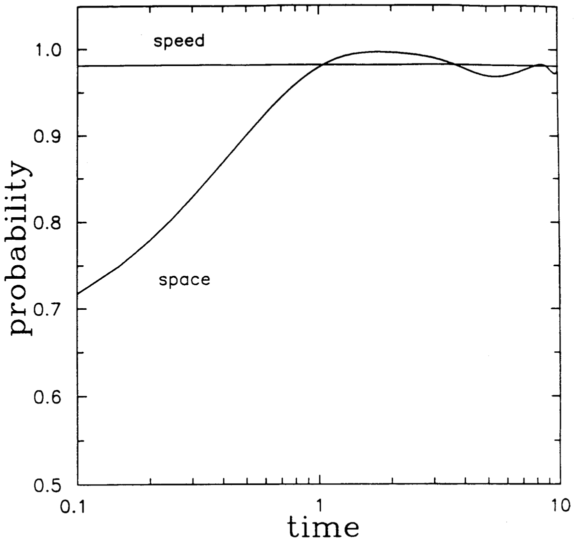

FIG. 2.—Spatial and speed probability as a function of past time. At each time the dispersion volume of the set of five particulate-disk stars was compared to 1000 sets of five chosen at random from the set of 17 control stars. The probability at that time is the fraction of cases for which the particulate-disk star set had a smaller dispersion than the control star set. As expected, the dispersion volume probability asymptotically approaches the constant dispersion velocity probability of 98%.

(≈ 10 km s^{-1}). As they age their dispersion increases toward that of the old Galactic disk population (Palous 1986; Palous & Piskunov 1985). We argue now that neither streaming nor youth can explain the small velocity dispersion of our particulate-disk star set.

Examples of streaming groups are the Sirius, Pleiades, and Hyades superclusters (Eggen 1983a, b, 1986, 1989). Half of all A stars within 25 pc are members of the Sirius superclusters and are moving on parallel orbits with a dispersion velocity of ≈ 1 km s^{-1} (Eggen 1989). Dispersions as large as that of our particulate-disk set (7, 6, 1) km s^{-1} are inconsistent with streamers from a cloud of plausible dimensions (< 100 pc) if the stellar ages are greater than 10^7 yr (Fig. 1). The ages of β Pic, α Psa, and α Lyr have recently been determined to be 1.0×10^8 yr, 2.0×10^8 yr, and 4.0×10^8 yr, respectively, with uncertainties of $\pm 1.0 \times 10^8$ yr (Backman & Paresce 1991). Further, this spread in ages is also an independent argument against a common origin.

The dispersion velocity of a large sample of field stars increases from (10, 10, 8) at ages less than 0.5×10^8 yr to (16, 11, 9) at ages 0.8–1.0 $\times 10^8$ yr (Palous 1986; Palous & Piskunov 1985). The particulate-disk star set has a W-velocity dispersion which is much less than that of the parent clouds of the field stars. Thus, although the ages of the three dated particulate-disk stars are somewhat less than that of the control set (1–4×10^8 yr vs. 1–10×10^8 yr), youth alone cannot explain the discrepancy in velocity dispersions.

If the particulate-disk stars are not conventional young streamers or young field stars, and are not a statistical anomaly, how can their small velocity dispersion be explained? Phenomenologically this could occur as an observational selection effect of randomly moving stars if these stars were "tagged" with particulate-disks when they passed through a distant, relatively localized, region of space. Their small velocity dispersion would then be the result of their being aimed at a target of radius 22 pc around the Sun. Stars enter and leave the tagging region in random directions but locally we see only those stars that were aimed at us and thus have small dispersion in the plane of the sky. One potential physical tagging volume is an interstellar dust cloud, which may enhance particulate-disk area through impact fragmentation of the circumstellar grains (Matese & Whitmire 1989). Before considering specific candidate clouds through which the particulate-disk stars may have passed, we first discuss the physical model.

4. MULTIPLE IMPACT FRAGMENTATION MODEL

In the solar system today it is believed that interstellar grains of size ~ 0.1 μm do not penetrate through the heliosphere located at 50–100 AU (Levy & Jokipii 1976; Holzer 1989). Modeling of the *IRAS* flux for the three prototype particulate-disk stars indicates that the inner edge of these disks lie roughly within this distance (Gillett 1986; BG; Matese et al. 1987). Interstellar dust is deflected by the perpendicular component of the solar wind magnetic field. Dust grains in the heliosphere are charged to $V \approx 5$ volt (Parker 1964; Lamy et al. 1985). The Lorentz and gravitational forces acting on a grain are respectively (Holzer 1989)

$$F_L \approx 1.5 \times 10^{-10} \text{ dyn } (u_E/10^7 \text{ cm s}^{-1}) a/R$$
$$F_G \approx 7 \text{ dyn } a^3/R^2 \,, \qquad (2)$$

where a is the grain radius, R is the heliocentric radial distance, and u_E is the solar wind flow speed at 1 AU. For $a = 10^{-5}$ cm, $R = 100$ AU, and $u_E = 5 \times 10^7$ cm s^{-1} the Lorentz force is 100 times the gravitational force.

Although today interstellar grains may not directly penetrate the heliosphere, during the passage of the Sun through an interstellar cloud of hydrogen number density $n_{\rm H} = 10^3$ cm^{-3} the solar wind is smothered beyond 1 AU (Begelman & Rees 1976). Thus it may be possible for the interstellar grains to penetrate the heliosphere precisely when this is relevant for our model. It is also likely that some nontrivial fraction of interstellar grains have radii greater than 1 μm and these grains could enter the heliosphere even today. Finally, depending on $n_{\rm H}$, the momentum exchange between gas and dust may allow the neutral gas to drag the dust inward notwithstanding the Lorentz force (Yabushita & Allen 1989).

There have been no positive measurements of stellar winds around main-sequence A stars and their winds could be less than the Sun's modest 3×10^{-14} $M_\odot$ yr^{-1}. Thus magnetic shielding of even the 0.1 μm size grains may not necessarily occur outside and especially inside clouds. Decreased magnetic shielding may in fact be indicated by a gap in stellar X-ray emission between spectral types B8 and A5 (Rosner, Golub, & Vaiana 1985). The absence of X-rays reflects an absence of surface activity and thus presumably mass loss. Curiously, all five of our particulate-disk stars fall within this range and all but one of the 10 particulate-disk A stars reported by BG and Aumann (1988) are also early A. The single exception (Gliese 673.1) listed by BG (and Gliese) as an A9 has been reclassified as an A3 m in a more recent listing (Backman & Paresce 1991). Of course, some observational selection is expected since particulate disks are more easily detected around the more luminous early A stars. Thus one cannot make a statistical statement regarding the significance of this observation. Nonetheless, it is noteworthy that the one star (α Aql) listed by BG as having no significant excess that passed through the same cloud as the particulate-disk star set (see below) is an A7, and therefore this anomaly may be explained by magnetic shielding. If magnetic shielding is relevant then these observations suggest that particulate disks around A stars are intrinsically different in origin or evolution than particulate disks around later spectral types since the early-to-late asymmetry is not apparent for the F, G, K spectral types.

The directly observed interstellar grains have radii ~ 0.1 μm (e.g., Greenberg 1978). Consistent with *IRAS* flux modeling, we assume that circumstellar grains are much larger than interstellar grains. In the solar system the interplanetary mass distribution has a broad peak centered near 100 μm (Grun et al. 1985). If the mass contained in ~ 100 μm size grains were collisionally fragmented into ~ 1 μm size grains the total grain area would be increased by a factor of the ratio of radii ~ 100. It is not likely that an interstellar grain of 0.1 μm can fragment a 100 μm circumstellar grain in a single collision (this might be possible if $\gtrsim 1$ μm interstellar grains exist). However, as is shown in the Appendix, multiple collisions by interstellar grains can cumulatively fragment the ambient circumstellar grains.

The zodiacal optical depth in the inner solar system today is $\sim 10^{-7}$ (Good, Hauser, & Gautier 1986). If this reservoir of mass in ~ 100 μm grains were fragmented down to ~ 1 μm sizes within the grain lifetimes (due to Poynting-Robertson drag and both internal and external terminal collisions) the optical depth could be increased to $\sim 10^{-5}$, which is within the range of optical depths given by BG for G-type stars. Of course, the solar system may also contain much more colder material beyond the planetary region at 100–150 AU (Aumann & Good 1990).

Once a newly fragmented circumstellar particulate disk is produced in a cloud, its evolution and lifetime depend on the nature and location of the original ambient particulate disk of large grains, the luminosity of the central star, the location and mass of any planets, and other uncertain variables. Thus, if the reported particulate disks are real, the apparent absence of velocity streaming in F, G, K spectral types may reflect a longer enhanced-disk lifetime due to the lower luminosities of these stars compared to A stars. Further, if a star is in a cloud long enough fragmentation may eventually begin to deplete particulate-disk area if the sources of the large grains (e.g., comets) do not replenish the grains faster than the removal time scale.

Multiple impact fragmentation can increase circumstellar particulate-disk area; however, erosion also occurs and this always decreases total area. The erosion or sandblasting of circumstellar particulate disks by interstellar dust clouds has been investigated by Lissauer & Griffith (1989). They found that the erosion rate for a single particule of radius a was $da/dt \propto V^3$, where V is the relative velocity. Since β Pic has the smallest random velocity relative to the LSR (≈ 4 km s^{-1}) of the 22 A stars in the Gliese catalog, they suggested that its usually large IR excess was due to the small erosion rate of primordial grains and its assumed young age. The correlation between small LSR velocity and IR excess was not considered significant for the remaining A stars with reported IR excess. As previously noted, recent age determinations indicate that β Pic, α Psa and α Lyr have ages in the range 1.0–4.0 × 10^8 yr. Erosion of particulate-disk grains must occur and compete with fragmentation. Based on the analysis given in the Appendix, if multiple impacts cumulatively contribute to fragmentation it can be shown that the fragmentation time scale is shorter than the erosion time scale.

5. ASSOCIATION OF PARTICULATE-DISK STARS WITH KNOWN INTERSTELLAR CLOUDS

The particulate-disk star centroid trajectory in the LSR is from the general direction of Libra (R.A. = 16^h0^m, decl. = $-14°$) whereas the centroid of control stars is from the general direction of Puppis (R.A. = 7^h38^m, decl. = $-28°$). The angle between these two velocity vectors is 112°. Heliocentric velocities and coordinates were taken from the Gliese and Bright Star catalogs and typical uncertainties in stellar velocities are 5%–10%. The Sun's (U, V, W) motion relative to the LSR was taken to be (10, 12, 7). The general direction of motion of the particulate-disk stars' centroid in the LSR suggested the possibility of an intersection with the extensive Scorpius-Ophiuchius southern cloud complex lying roughly in the 4th quadrant between $l = 270°$ and 360° (Frisch & York 1983, 1986). The associated Lupus-Centaurus star concentration is located between $l = 290°$ and 350° and $b = +5°$ to $+25°$ (Eggen 1983a). The narrow Z extension of this cloud relative to its other dimensions also showed it to be consistent with the kinematical model.

To investigate the possibility of intersection we transformed to a frame at rest with the Lup-Cen concentration. We focus on the star concentration rather than the larger cloud complex since the heliocentric space velocity (6, 25, 8) of the concentration is better known (Eggen 1983b). To model the cloud we used Lup-Cen concentration coordinates and velocity, and it was assumed that the cloud extends radially from 80 to 150 pc (Frisch & York 1983, 1986). The resulting projected trajectories in the cloud/concentration frame are illustrated in galactic X, Y, Z coordinates in Figures 3 and 4.

These figures taken together show the three-dimensional trajectories of the particulate-disk (*filled circles*) and control (*open*

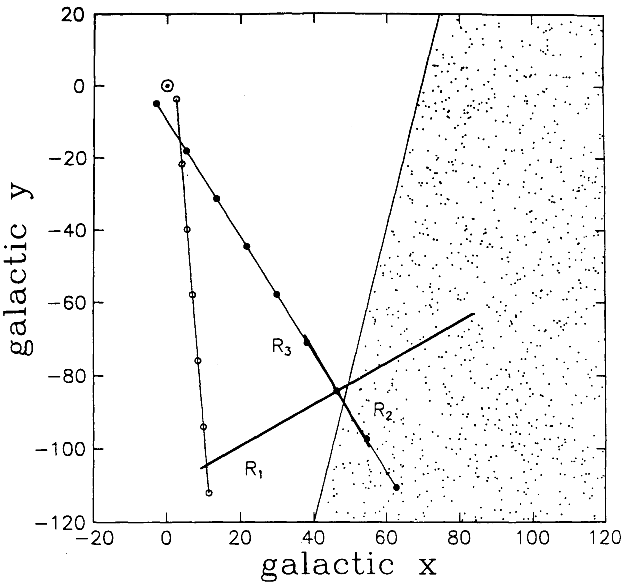

FIG. 3.—The past trajectories of the centroids of the particulate-disk (*filled circles*) and control (*open circles*) star sets projected onto the galactic X, Y plane. Dotted region is the model cloud projection. The positions are plotted at intervals of 1 Myr beginning at their present positions near the Sun. Darker lines labeled R_1, R_2, R_3 are the projections of the three principal axes of the particulate-disk star ellipsoidal dispersion volume shown immediately after emerging from the cloud. This figure along with Fig. 4*a*, *b* determine the three-dimensional motion of the two centroids in the cloud.

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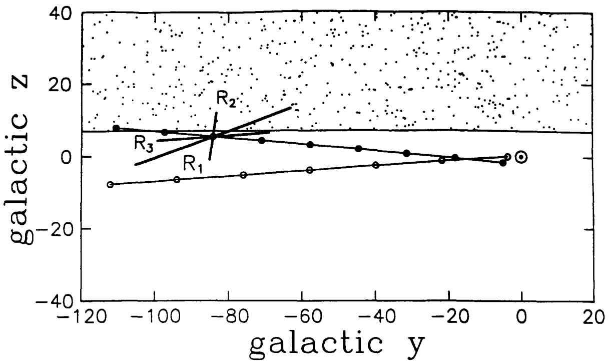

FIG. 4*a*

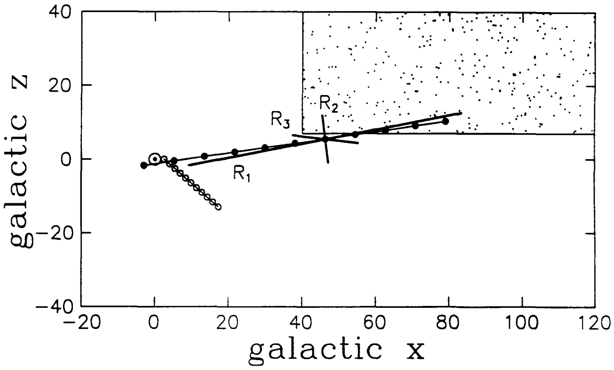

FIG. 4*b*

FIG. 4.—(*a*, *b*) The past trajectories of the centroids in the galactic Y, Z and X, Z planes. Symbols are the same as Fig. 3.

circles) stars' centroids backward in time at intervals of 1 Myr. The present position of the centroids is near the solar symbol. The darker lines labeled R_1, R_2, R_3 are the projections of the three principal axes of the ellipsoidal dispersion volume shown immediately after the particulate-disk star centroid left the cloud. Figure 1 can be used to estimate the dispersion volume at other times.

It can be seen from these figures that, within the uncertainties in cloud velocity, boundaries (the cloud contour was assumed constant during the past 10 Myr), and two-body perturbations, the particulate-disk stars' centroid passed through the lower part of the Lup-Cen cloud. The control stars' centroid did not enter the cloud and was in the opposite galactic hemisphere from the cloud in the recent past. In terms of individual trajectories, four of the five particulate-disk stars passed through or very near the bottom of the modeled cloud and one star passed somewhat farther below. Of the 17 control stars only three passed as close to the cloud as the particulate-disk stars. Two of these controls (α Pic and Gliese 673.1) are listed as stars with Vega-like IR excess by BG. The third control (α Aql) is a late A7 star and may have been shielded by a stellar wind magnetic field as previously discussed.

6. CONCLUSIONS

In summary, we have discovered statistically significant velocity streaming in the set of the most secure *IRAS* main-sequence particulate-disk stars. Monte Carlo simulations showed that streaming at this level would occur by chance in only 2% of the cases. It is argued that this streaming is not due to a common origin or youth but instead is the result of observational selection in a model in which the circumstellar particulate-disks are enhanced by passage through interstellar clouds. Association of the centroid trajectory of the particulate-disk stars with the Lup-Cen cloud/concentration complex is suggestive but, because of uncertainties, inconclusive.

The kinematical model predicts that the velocity streaming of particulate-disk stars will diminish for distances well beyond 22 pc. At the cloud distance of ∼100 pc and beyond particulate-disk stars should not exhibit streaming but their trajectories should intercept the same Lup-Cen cloud. However, if the local streaming of particulate-disk stars is due to youth, it should persist at distances greater than 22 pc. Such a test may be possible using an updated list of main-sequence particulate-disk stars in the Bright Star Catalog (D. Backman, in preparation).

We thank Dr. Dana Backman for supplying us with data prior to publication and other assistance and Dr. Olin Eggen for helpful comments. The support of a NASA/Ames Research Center University Consortium grant and a grant from the Louisiana Educational Quality Support Fund is also recognized.

APPENDIX

We wish to estimate the maximum radius of a particulate-disk grain, $R_{\rm max}$, which can be disrupted by cumulative impacts of interstellar cloud grains of radius r having an impact velocity V. Gault & Wedekind (1969) have demonstrated that multiple impacts are as effective as single impacts in rupturing a target if the same total energy per unit mass, E_R, is transferred.

Thus, after γ impacts, target masses less than M will be disrupted by a projectile m where

$$M = mV^2\gamma/2E_R$$

or (A1)

$$R = r[\gamma V^2/2E_R]^{1/3}$$

if the grains have comparable density. Observed interstellar grain sizes are typically in the range 0.05–0.25 μm. The results of many experiments on varied materials suggest that $E_R \approx 10^7$ ergs g^{-1} (Grün et al. 1985). What is most uncertain is the maximum number of impacts, $\gamma_{\rm max}$, for which equation (A1) is valid. Gault & Wedekind (1969) have demonstrated its validity for $\gamma < 19$ and have suggested that a conservative limit is $\gamma_{\rm max} = 10^2$. Inserting these estimates into equation (A1) gives

$$R_{\rm max} = 50\ \mu{\rm m}\ (r/0.15\ \mu{\rm m})(V/25\ {\rm km\ s^{-1}})^{2/3} \times (E_R/10^7\ {\rm ergs\ g^{-1}})^{-1/3}(\gamma_{\rm max}/10^2)^{1/3}\ . \quad {\rm (A2)}$$

The time scale to cumulatively rupture a target $R_{\rm max}$ after $\gamma_{\rm max}$ collisions is

$$\tau = \gamma_{\rm max}/\pi R_{\rm max}^2 n V \quad {\rm (A3)}$$

where n is the number density of interstellar cloud grains,

$$n = 10^{-2} n_{\rm H} m_{\rm H}/(4\pi r^3 \rho/3)\ , \quad {\rm (A4)}$$

and $n_{\rm H}$ is the mean hydrogen number density. We have assumed that the grain spatial density is 1% by mass and adopt $\rho = 3$ g cm^{-3}. Combining equations (A2–A4) we find

$$\tau = 5 \times 10^4\ {\rm yr}\ (\gamma_{\rm max}/10^2)^{1/3}(V/25\ {\rm km\ s^{-1}})^{7/3} \times (r/0.15\ \mu{\rm m})(n_{\rm H}/1\ {\rm cm^{-3}})^{-1}(E_R/10^7\ {\rm ergs\ g^{-1}})^{2/3}\ . \quad {\rm (A5)}$$

Alternatively the hydrogen column density required to accumulate $\gamma_{\rm max}$ collisions is

$$N_{\rm H} = 4 \times 10^{18}\ {\rm cm^{-2}}(\gamma_{\rm max}/10^2)^{1/3}(V/25\ {\rm km\ s^{-1}})^{-4/3} \times (r/0.15\ \mu{\rm m})(E_R/10^7\ {\rm ergs\ g^{-1}})^{2/3}\ . \quad {\rm (A6)}$$

To summarize, for the adopted parameters, we estimate that stellar particulate-disk grains up to $\sim 50\ \mu$m can be disrupted by the cumulative deposition of energy from $\gamma_{\rm max} = 10^2$ impacts of interstellar dust particles. For a mean hydrogen number density $n_{\rm H} =$ 1 cm^{-3} the time to accumulate $\gamma_{\rm max}$ impacts is approximately 5×10^4 yr during which the stellar system will move a distance of ≈ 1 pc through the cloud at a speed of 25 km s^{-1}. Independent of the mean cloud density, the column density required to accumulate $\gamma_{\rm max}$ collisions is estimated to be $N_{\rm H} \approx 4 \times 10^{18}$ cm^{-2}. The evolution of a particulate-disk after it has been collisionally enhanced depends on removal time scales as well as fragmentation time scales. In voids or bubbles outside clouds $n_{\rm H}$ can be as low as $\sim 5 \times 10^{-3}$ cm^{-3} and the time scale for fragmentation would be correspondingly longer. Today the column density between the Sun and the nearest edge of the Lup-Cen cloud is $\sim 5 \times 10^{18}$ cm^{-2}. However, the particulate-disk stars have not necessarily been within regions of this density since leaving the cloud. Finally, we note that single impact fragmentation may also be relevant depending on the size distribution of interstellar grains. Grains with radii $r > 1\ \mu$m may be capable of fragmenting $\sim 100\ \mu$m circumstellar grains in a single collision.

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