# ON THE GENETIC RELATION BETWEEN INTERSTELLAR CLOUDS AND DUST CLOUDS

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**Abstract.** We propose that many of the denser dust clouds represent transient stages between the initiation of gravitational collapse of ordinary interstellar clouds by passage through a spiral galactic shock and the appearance of a stellar association. The interstellar gas is not processed at too rapid a rate (1) because the time spent between galactic shocks is appreciably longer than the free-fall collapse time of a typical dust cloud, and (2) because only a small fraction of the total mass of gas of a given collapsing cloud is converted into stars – the rest is presumably redispersed by various dynamical processes which accompany the formation of massive stars. We note that the residue of atomic hydrogen observed to exist in dark dust clouds is compatible with the interpretation that they are transient objects whose lifetimes are not longer than $\sim 10^7$ yr.

It can hardly be disputed that the self-gravity of a dust cloud is considerable. What has not been settled, either observationally or theroretically, is whether the darker dust clouds (with $A_v > 1$ or 2) represent stable dynamical objects, which are supported by rotation or by other means, or whether they represent transient objects, which exist only as temporary stages in the history of the formation of a cluster of stars from ordinary interstellar clouds. I shall take the latter view here.

In particular, I wish to pursue the possibility that isolated dust clouds are in state of dynamical collapse, whereas dust clouds in regions of active star formation may eventually be redispersed by various dynamical processes. In any case, the lifetimes of such clouds cannot greatly exceed $10^7$ yr.

Such a conclusion would be important not only for its implication on the problem of star formation but also for the natural time scale it would impose on physical processes such as the formation of interstellar molecules. To date, theoretical calculations of the formation of molecules in dark clouds have generally assumed that the molecular concentrations of each species has sufficient time to reach an equilibrium in which the rate of formation is just balanced by the rate of destruction. In fact, the time scale associated with the rate-limiting reactions are often comparable or longer than the free-fall collapse time for a typical dust cloud. We shall see later that this circumstance allows, in principle, a 'dating technique' to investigate whether isolated dust clouds are, in fact, undergoing collapse.

## 1. Rate of Processing of Interstellar Gas

Let us first summarize the primary indirect arguments for and against the view that isolated dust clouds are collapsing gravitationally. The following argument *against* collapse, brought to my attention by G. B. Field, is perhaps the most serious.

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Hollenbach *et al.* (1971) have estimated from Beverley Lynds' (1962) catalogue that 20–40% of the gaseous matter in the local interstellar medium is in the form of dark clouds with visual extinction $A_v \geqslant 1$ mag. The free-fall collapse times for such clouds can be estimated to be about a few million years. A major dilemma would obviously result if 20–40% of the interstellar medium were processed into stars every few million years.

I believe the resolution of this dilemma can be found by examining a photograph of an external spiral galaxy such as M51. As is well-known (Lynds, 1970, 1972), the dark lanes in such galaxies are typically not found everywhere but are generally confined to the inside edges of the optical spiral arms. In the density-wave theory of spiral structure, the explanation is as follows.

The spiral structure owes its existence to a spiral density wave. In the frame which rotates with the speed of the wave pattern, the interstellar gas flows through the pattern and is strongly concentrated in the spiral arms – in many cases, as shown by Roberts (1969), by galactic shocks. The high space density reached in the post-shock region is associated with the dark lanes.

It is tempting to suppose that dense clouds are *formed* in the high-compression region behind the galactic shock; however, the existence of the dark lanes does not, *by itself*, provide a proof. There are, logically, two separate aspects of the large-scale compression: (1) the concentration of an aggregate of cloud centers into a smaller volume, and (2) the compression of each individual cloud to greater internal densities. If the gas to dust ratio remains constant, only the first process leads to an increase of the *average space density* and, thus, to an increase of the visual extinction. The compression of *individual clouds*, leading in some cases to gravitational collapse and to the formation of stars, is inferred from the concentration of giant H II regions a little downstream from the dark lanes.

A specific calculation of these effects in the context of the two-phase model of the interstellar medium was carried out recently by a number of us (Shu *et al.*, 1972). The results for the cloud phase along a streamline passing through the solar neighborhood is shown in Figure 1. Immediately after a galactic shock, the ordinary interstellar clouds have an average internal density of $\sim 50 \text{ cm}^{-3}$ if we ignore the effects of their self-gravity. They occupy $\sim 5\%$ of the volume of interstellar space. With the usual gas and dust parameters, this results in a visual extinction of $\sim 4$ mag. kpc$^{-1}$. (A minimum extinction of $\sim 0.4$ mag. kpc$^{-1}$ is reached in between spiral arms.) At the post-shock density of $50 \text{ cm}^{-3}$, a $400\, M_\odot$ spherical cloud would provide $\sim 0.5$ mag. of extinction along a diameter. This would not qualify it as an especially dark cloud. However, if we consider the self-gravity of this same cloud, the calculated internal temperature of $\sim 30$ K would not be sufficient, in the absence of other stabilizing influences, to prevent the cloud from collapsing under the load of the ambient intercloud medium. Indeed, our calculations indicate the mass threshold for collapse in the post-shock region to be only $120\, \text{M}_\odot$ if only the gas kinetic pressure is available to support the cloud.

It is not unreasonable, then, to suppose that a significant fraction of the ordinary

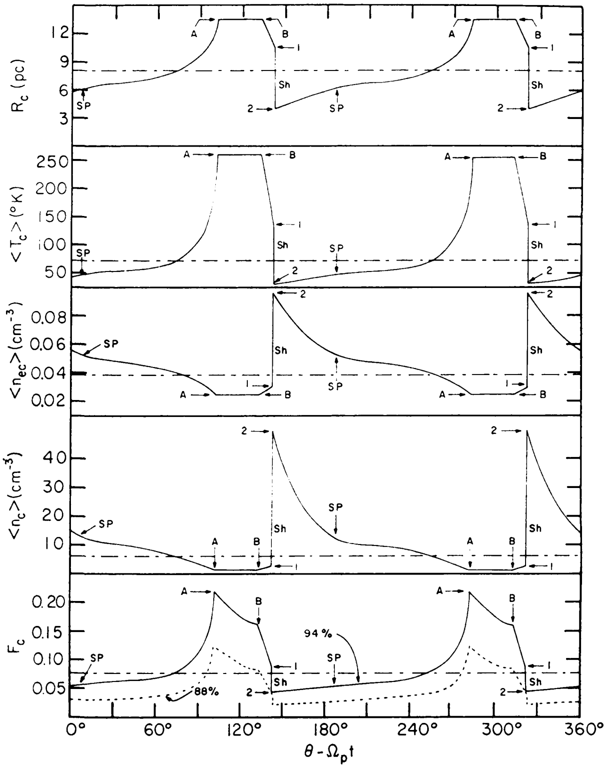

Fig. 1. The variation of the properties of the cloud phase along a streamline which passes through the solar neighborhood. From top to bottom, the curves give, respectively, the radius of a 400 $M_\odot$ cloud, the average internal temperature of the clouds, the average electron density inside the clouds, the average internal density, and the fraction of volume of interstellar space occupied by the aggregate of clouds. The solid curve for $F_c$ corresponds to a space density of 0.5 cm$^{-3}$ when averaged over the streamtube; the dashed curve, to half this value.

interstellar clouds are induced to collapse gravitationally – say, for sake of argument, a fraction even as large as to constitute 20–40% of the gaseous mass of the local interstellar medium. (The number, 20–40%, is illustrative. The Sun is probably not located immediately behind a primary galactic shock, and the dust clouds in the immediate neighborhood of the Sun may owe their origin to the presence of the local spiral arm.)

It would still be embarrassing if we were to conclude that 20–40% of the interstellar medium is converted into stars per galactic shock since the time spent between galactic shocks is only $2.7 \times 10^8$ yr at the solar circle. Fortunately, radio observations show that the mass of the gas associated with young stellar associations is often more than ten times larger than that contained in the form of stars (cf. Menon, 1962; Raimond, 1965; and others). This supports various theoretical considerations which suggest that the process of star formation is not highly efficient so that the collapse of any given cloud results in only a few percent of the total gaseous matter being converted into stars. Presumably the rest is redispersed by expanding H II regions, by supernovae explosions, and by other dynamical effects which accompany the formation of massive stars.

If we now adopt an efficiency of star formation as high as 10% and the collapse of a healthy fraction of the clouds per galactic shock, we obtain a net conversion of 10% × 20–40%/2.7 × $10^8$ yr = 1–2% of the interstellar gas into stars every $10^8$ yr. Such a rate is in reasonable accord with the observations. We have resolved the dilemma posed at the beginning of this section simply by noting that the collapse of *individual* dust clouds does not constitute the rate-limiting process for the conversion of interstellar gas into stars.

## 2. Formation of Molecular Hydrogen in Collapsing Clouds

Apart from direct observational studies of the internal kinematics of dust clouds, how may we determine whether isolated dust clouds are truly collapsing ? A promising method seems to be the use of the small residue of atomic hydrogen detected in dust clouds as a probe of their previous history. In fact, any relaxation phenomenon having a characteristic time scale of $10^6$ yr or longer could serve a similar capacity. The conversion of atomic hydrogen into molecular form turns out to be convenient for ascertaining the density history of the cloud because the process happens to be insensitive to the temperature.

The most complete survey for atomic hydrogen in dust clouds, of which I am aware, is contained in Knapp (1972). Shown in Figure 2 is a reproduction of her results for 28 dust clouds seen in 21-cm line absorption. The column density $N_H$ deduced from a narrow absorption feature is plotted against the average visual extinction $A_v$ produced by the cloud. Knapp's analysis ignores the possible presence of foreground hydrogen in emission over the frequency interval of the absorption feature; thus, her data points may underestimate the amount of atomic hydrogen actually present in the dust clouds.

The curve labelled $N_H = 2 \times 10^{21} A_v$ represents the value expected from simply extrapolating the gas to dust ratio found in the general interstellar medium. The difference between it and the plotted points presumably represents the amount of atomic hydrogen converted to molecular form.

The other curves labelled UV, CR, FFC, etc. have been superimposed by me to illustrate possible theoretical explanations. In the curves labelled UV, CR, and FFC, formation of $H_2$ is assumed to take place on grain surfaces with the rate given by Hollenbach *et al.* (1971). The curve labelled UV, which is taken from their paper, gives the column density of atomic hydrogen to be expected for a 2000 $M_\odot$ dust cloud at various densities if the cloud is assumed to be in equillibrium with the ultraviolet radiation fiield present in interstellar space providing a dissociation of $H_2$. Since 2000 $M_\odot$ corresponds to a fairly large dust cloud, it is probably safe to conclude that the residue of atomic hydrogen present in the darker clouds effectively rules out the possibility that these dust clouds could be in static equilibrium with UV providing the main mechanism of dissociation of $H_2$.

The dashed curve labelled CR gives the equilibrium column density of atomic hydrogen for a 120 $M_\odot$ cloud when low-energy cosmic rays are assumed to provide the mechanism of dissociation of $H_2$. The computation proceeds along the lines of

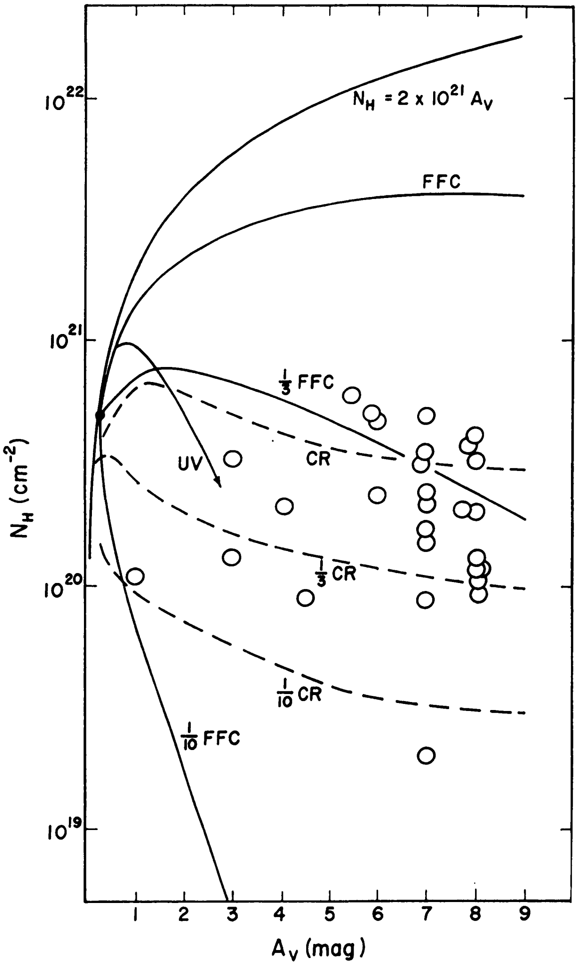

Fig. 2. The column density of atomic hydrogen along an average line of sight (spanning a length equal to $\frac{4}{3}$ times the radius if the cloud is spherical) as a function of the average visual extinction produced by the dust cloud. The curve labelled $N_{\mathrm{H}} = 2 \times 10^{21} A_v$ is the relation found for the general interstellar medium; the data points are from Knapp (1972); the curved labelled UV is computed for a 2000 $M_{\odot}$ cloud; and the other curves are computed for a 120 $M_{\odot}$ cloud. See the text for other explanations.

Solomon and Werner (1970), but the flux of cosmic rays has been taken to have the value deduced by Hughes *et al.* (1971) from their study of the ionization level in ordinary interstellar clouds. The other dashed curves labelled $\frac{1}{3}$CR and $\frac{1}{10}$CF assume the ratio of the rates of cosmic-ray dissociation to molecule formation to have $\frac{1}{3}$ and $\frac{1}{10}$ the value adopted in the curve CR. Although self-shielding of the dust clouds from the external flux of low-energy cosmic rays may lower the dashed curves appreciably, we see that the curves labelled CR and $\frac{1}{3}$CR give a reasonable accounting of Knapp's observations.

The remaining curves give the locus of collapsing clouds of 120 $M_{\odot}$ which start from rest at a density of 50 $\mathrm{cm}^{-3}$ with zero molecular hydrogen present initially. (The details of the calculation will be published elsewhere). The curves do not follow $N_{\mathrm{H}} = 2 \times 10^{21} A_v$ because of the subsequent formation of $\mathrm{H}_2$. Dissociation of $\mathrm{H}_2$ by ultraviolet radiation and by low-energy cosmic-rays can be ignored when the collapse is sufficiently rapid because the rate of formation of $\mathrm{H}_2$ is much greater than the rate of destruction in this non-equilibrium situation.

The curve labelled FFC is computed for a uniform sphere undergoing free-fall collapse. This gives the shortest possible time scale for the collapse if external loading is not considered. The curves labelled $\frac{1}{3}$FFC and $\frac{1}{10}$FFC assume the ratio of the rates of collapse to molecule formation to have $\frac{1}{3}$ and $\frac{1}{10}$ the value adopted in the curve FFC. Such adjustments may be necessary because the total grain surface area available to form molecules may be substantially larger than the value adopted by Hollenbach *et al.* if there truly exist many interstellar particles of very small dimensions (cf. Lillie and Witt, 1973; Witt, 1973), or because the collapse time is lengthened by partial support from gas pressure, rotation, turbulence, or internal magnetic fields.

The results displayed in Figure 2 verify the assertion of Hollenbach *et al.* that gravitational collapse is unlikely to keep the darker dust clouds from becoming mostly molecular; but more importantly, they show that collapse may be the primary factor which determines the amount of atomic hydrogen left in isolated dust clouds. Thus, an interpretation, alternative to dissociation of $\mathrm{H}_2$ by low-energy cosmic-rays, for the relatively large residue of atomic hydrogen observed by Knapp is that the darker dust clouds are transient objects with lifetimes shorter than $\sim 10^7$ yr. We favor the latter interpretation because we believe the large molecular line-widths observed in many isolated dust clouds may well be associated with collapse velocities.

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