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COMETS, INTERSTELLAR CLOUDS AND STAR CLUSTERS

B. Donn

It is now a generally accepted concept that comets are a residue of the early history of the solar system from the time when the planets were forming. Because of the approximately 0.1% loss of material from the nucleus during perihelion passage near 1 A.U., lifetimes of short period comets are limited to 10^4-10^5 years. This requires an astronomically recent source of the comets seen at the present epoch. From the statistics of the aphelia of parabolic and long period comets, Oort (1951) proposed the existence of a comet cloud between 50,000 and 100,000 A.U. which serves as a reservoir from which presently observed comets have recently been perturbed. Although there are various difficulties with populating the cloud (Opik, 1973) and its subsequent evolution (I.A.U. Symposium 45, 1972; Everhart, 1974) it is the basis for nearly all current studies on the origin and evolution of comets.

At heliocentric distances of tens of thousands of A.U. the density of matter in a solar nebula isolated in space was much too small to allow for the accumulation of cometary size objects. Until recently, all theories of star formation or planetary origin have assumed that the Sun formed as an isolated single star. Cameron (1973) in an analysis of planetary accumulation, postulated massive fragments breaking off from the outer limits of the primordial solar nebula and revolving around it. He proposed these sub-clouds as the regions where comets could form at distances comparable to Oort's cloud. This theory was based on his theory of the evolution of a solar mass fragment of a collapsing interstellar cloud (Cameron , 1973).

This paper develops further the proposal I made (Donn, 1973) that comet formation occurs in fragmenting interstellar clouds in which star clusters form. Evidence for continual star formation in the galaxy is now so well established that it can no longer be questioned. This evidence has been described in several places, e.g. Spitzer (1968) and is only concisely reviewed here. (1) The very luminous O and B stars are consuming their nuclear energy at a rate that will permit them to continue to maintain their present characteristics for a time of the order of 10^6 years; (2) a similar result is obtained for the ages of young clusters from the position in the Hertzsprung-Russell diagram where the stars show evolution off the zero age main sequence line; (3) expansion of OB associations yield dynamical ages of similar duration; (4) irregular variables with emission lines among spectral classes G and K, the T Tauri stars, are intimately associated with heavy obscuration, frequently in conjunction with OB stars. These objects seem to be stars that have only recently undergone gravitational contraction to the main sequence (Herbig, 1962).

Observed newly formed stars tend to occur in clusters and some theoretical analyses have indicated that all star formation occurs in large groups of a hundred to about one thousand stars (Roberts, 1957; Ebert, et al. 1969). On the other hand, Aveni and Hunter (1967) have found four early-type stars that they could not attribute to known clusters or associations. They have proposed (Aveni and Hunter, 1969, 1972) that OB and T Tauri stars can form in condensations of 100 or less solar masses. Herbig (1970) believes that stars may form in small groups, possibly as single objects.

It is very likely that the Sun formed some $6x10^9$ years ago as a member of a cluster. During that interval this cluster has presumably disintegrated. In this regard, the oldest galactic clusters (Iben, 1967) are $10x10^9$ yrs for NGC 188 and $5x10^9$ yrs for M67. In a developing cluster the conditions for comet formation are not restricted to within fifty A.U. of the Sun. Indeed, matter of appreciable density is distributed over a volume with dimensions of several parsecs. This is shown in photographs of gas and dust distribution for young clusters and regions showing good evidence of star formation.

Although theoretical investigations of cloud fragmentation are still in an early, controversial state, there is general agreement (Larson, 1973) on the occurring of fragmentation. Observationally, clusters do exist and their association with gas and dust is clear evidence of star formation in clusters via fragmentation. Theoretical investigations (Salpeter, 1959; Hartman, 1970) lead to mass functions varying as M^{-b} where b is between 1 and 1.5. This relation fits the star distribution near the Sun down to a few tenths solar mass (Hartmann, 1970). Beyond that point stellar luminosity functions begin to decrease although the behavior for small masses is uncertain. The smallest measured stellar mass is Ross 614B, $M_v = 16.8$,

$M = 0.07\ M_\odot$ (van de Kamp, 1971). In the Hyades, the nearest open cluster, the faintest stars have $M_V = 17$ (von Altena, 1966). Greenstein, et al. (1970) concluded that the faint end of the main sequence is bounded at $0.09\ M_\odot$. This value shows good agreement with the theoretical lower limit $0.085\ M_\odot$ (Hoxie, 1970; Straka, 1971a,b). It appears that a real minimum stellar mass of about $0.07\ M_\odot$ exists. This limit is the result of an instability to produce nuclear energy and cloud fragments of such mass may yield massive condensations. The collapse of these and small fragments does not appear to have been investigated. It is rather likely that such small masses in a cluster either intrinsically or because of nearby star formation cannot collapse to stars. However, such fragments are expected (Cameron 1973; Larson 1973). For the smallest mass clouds they will exceed the stellar mass function and almost certainly peak at smaller masses.

In the smallest fragments the density may be large enough and the temperature cold enough that volatile material condenses. This may occur homogeneously as well as on existing non-volatile grains. Under these conditions, efficient accumulation of larger solid objects could occur. In his analysis of the evolution of cloud fragments from a few solar masses to a fraction thereof, Cameron's (1973) analysis suggests that accumulation of cometary nuclei in the range 10^{14}-10^{20} gm will be a rapid process.

Within the volume of the cluster will be many regions where comets may form. Their composition will be that of the interstellar molecule population in each subcloud. The complex molecular array in Orion is highly concentrated toward the region of the Beklin-Neugebauer infrared source. Formaldehyde has a broader distribution and carbon monoxide is still less concentrated. Water is only detectable in maser sources but its cloud distribution presumably is intermediate between carbon monoxide and formaldehyde. The composition of the nuclei formed depends upon the effectiveness of molecule formation in the region. This in turn probably depends upon the availability of energy sources (Donn and Stief, 1974). Cometary nuclei may form with variable ratios of three classes of constituents; CO, H_2O: complex organic molecules: dust. The spectra of new comets actually fall into these three classes, i.e. "new" comets in which each type of material predominates are known: continuum strongest; molecular emissions dominate or CO^+ dominates.

Some description of the possible evolution of the comet cloud can be given. Within clusters and associations the velocity dispersion is less than 3 km/sec (Blaauw, 1964). For subclouds in the proximity of a particular star, turbulence theory suggests that relative velocities will tend to be less than for the cluster as a whole. Consequently, comets forming within a fraction of a parsec of a star will have average relative velocities of perhaps 1 km/sec. The velocity dispersion within a comet cloud can be expected to be comparable or greater.

In a cluster the average distance between stars is about 0.5 pc. It is to be noted that this distance is significantly smaller than the 2.2 pc mean distance (van de Kamp, 1971) for stars presently within 5 pc of the sun. As a result for comet formation in clusters, the stability and early evolution of the comet cloud differs from similar features of the standard Oort cloud. Comets having near zero velocity relative to the Sun and within about 0.1-0.3 pc or 20-60x10^4 A.U. would be the primary members of the cloud. Because of stellar perturbations within the cluster, resistance effects and non-gravitational effects caused by radiation or stellar winds within the cluster, comets with higher velocities or at larger distances might have become members of the Sun's cloud. Tinsley and Cameron (1974) have proposed that a large number of interstellar comets could act as sinks of heavy elements and in this way explain the slow rate of heavy element buildup in the galaxy. Greenberg (1974) has also proposed that comets may account for interstellar deficiencies of heavy elements.

The association of comets with star formation in clusters seems a natural development. This hypothesis also provides prospects for explaining the origin and evolution of the Oort cloud, the composition of comets, and relationships between cometary and interstellar molecules. It also suggests that comets allow us to study interstellar matter close to the sun. According to this hypothesis, a comet probe would be an interstellar probe as well.

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DISCUSSION

L. Biermann: The reason for expecting many more cometary nuclei in interstellar space than in the Oort clouds of stars like our sun is a quite general one. The total energy per gram of such an object must be negative but only by a quite small amount. Irrespective of the exact place of first formation, the solar system or outside of it, but in that dense interstellar cloud in which here and there a star is being born, the probability of such an object ending up in the Oort cloud with such initial parameters that it stays there for 10^9 years is only of order some percent or less. Since this point was the subject of a contribution of mine at the 1972 Nice Colloquium on the Origin of the Solar System, I shall not elaborate it further. In closing I should say only that it is a least conceivable that a sizeable fraction of the interstellar C, N, and O atoms are tied up in such objects (not necessarily of 10^{-16} gm or more) a possibility currently being discussed in connection with the chemistry of interstellar space (M. Friesberg, 1974).

J. T. Wasson: I think that many of the arguments that you give for believing that interstellar material will give you high CH_3CN or CH — or methyl acetylene, whatever ratios, are quite correct but I'm also not convinced that you can't get them by material forming close to the sun.

I think that we don't know, first of all, anything about the temperature distribution in the early solar system: even though it undoubtedly got fairly hot in near to the sun, we don't really know how hot it must have gotten out at 30 astronomical units during, say, the collapse phase of the solar nebulae.

Secondly, we don't know that all the matter in the solar system fell in at once. It may have been a very gradual process of material being captured by the solar system from the interstellar cloud. One could certainly imagine a model where half or more of the material that ultimately ended up at ten astronomical units from the sun or every further out was in fact interstellar material that had never been hot and had never, therefore, lost the inner stellar signature that you've been talking about.

B. Donn: It is certainly true. I wouldn't insist that this is necessarily a unique distinction but we know in the interstellar medium that these complex compounds have in fact surprisingly high concentration compared, to any CO and H_2.

In the solar nebulae it is true we don't know. Most of the theoretical calculations have assumed that it is near an equilibrium calculation. It may not be. And so it may be that when you get these observations, you will not be able to make a unique determination. But I think it is one possibility.

The isotope ratios may be a little bit better but again, the same sort of thing may apply if the material falling into the solar system was again not recycled to bring about equilibrium.

J. T. Wasson: I think most of these calculations have been done by meteoriticists who believed they were talking about material that formed at about 2.8 astronomical units.

M. Oppenheimer: Along the same line, in line with Dr. Whipple's model, there's a way that comets forming at very large distances can be characterized by a signature of high temperature formation. It gets very complicated because that's sort of a region which is neither here nor there.

And also, with respect to the deuterium problem, the thing that determines the hydrogen to deuterium ratio in those molecules is the energy defect as far as the exothermicity of reactions like $HD + HCN \rightarrow H_2 + DCN$, which are a few hundred degrees, and you have to be very careful that as the densities become very high as this matter conglomerates—even if the temperature never gets a above 100 or 150, the time scales are going to become short enough so that you may wipe out the original signature, and when the hydrogen is blown out of the object that becomes a comet, that difference may just totally disappear.

So I think it is something that has to be worked out very carefully.

B. Donn: I agree. What I'm proposing here is not that this is a definite, unique phenomena but that both the observations and the whole theory of molecular formation should be looked at from this point of view to see what happens.

And of course to do these observations in comets is certainly intrinsically significant and would be very worthwhile. If one does find, for example, distinction among comets for example, different ratios, that could be a useful clue.