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Capture of field stars by molecular clouds

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Summary. Field stars can be captured by massive interstellar clouds. Stars encounter interstellar clouds with relative velocities that have a distribution. Close encounters in which stars enter a cloud with relative velocities less than the escape velocity result in gravitational capture of the stars by the cloud. Using typical values for the parameters characterizing the molecular clouds and the field stars of different types, the numbers of the captured stars are estimated, which are found to be significantly large to have observable consequences. When star formation in the cloud gives rise to the formation of a star cluster, it would contain two populations of stars: the young newly born stars and the older field stars that were captured by the cloud during its long life time prior to star formation. It is suggested that the very low mass stars on the main sequence of the Pleiades cluster and evolved stars occupying anomalous positions on the colour-magnitude diagrams of some other young clusters are captured field stars.

Key words: interstellar clouds: kinematics – stars: kinematics – stars: clusters

1. Introduction

Molecular clouds are an important component of the interstellar medium. A significant fraction of the interstellar matter is contained in these dense and cold clouds, and new stars and star clusters are born from them. The clouds show a large range in mass (M_c), from a few $M_\odot$ for the small Bok globules to $\sim 10^6 M_\odot$ for the Giant Molecular Clouds (GMCs). There are an estimated $\sim 10^4$ GMCs with $M_c \gtrsim 10^5 M_\odot$ in the Galaxy (Sanders et al., 1985). The GMCs are the most massive objects in the Galaxy and represent the upper end of a power law cloud mass spectrum of the form: $dN/dM \propto M^{-1.5}$ (e.g. Bhatt et al., 1984; Casoli et al., 1984), where dN is the number of clouds with mass between M and $M + dM$. The larger clouds have internal substructures and then M includes the mass of the substructures also.

Because of their large masses the GMCs play an important role in the dynamics of the galactic disc. Spitzer and Schwarzschild (1951, 1953) showed that gravitational interaction between stars and massive interstellar clouds increases the velocity dispersion of the stars with advancing age. In these interactions the contribution to the increase in the velocity dospersion of stars is dominated by the cumulative effect of distant encounters, so that close encounters in which stars penetrate the cloud are neglected. While the majority of field stars are accelerated due to distant encounters with the clouds, a small fraction of the field stars that do pass through the clouds can also experience important physical effects. Thus stars, during their passage through the cloud, can accrete matter and also be decelerated (Bondi and Hoyle, 1944). The magnitude of these effects depends on the relative velocity between the star and the cloud, and is quite small for an average field star.

A cloud can also capture a field star gravitationally if the star enters the cloud with a relative velocity less than the escape velocity at the cloud surface. Field stars have a distribution of peculiar velocities with respect to the local standard of rest. From a distribution of velocities only a small fraction of field stars would have velocities, relative to the cloud, smaller than the escape velocity and be captured by the cloud during a penetrating encounter. However, as will be shown in this paper, over the long life time of the cloud, a substantial number of field stars can be captured by a massive cloud. In Sect. 2, we derive the rate of capture of field stars by molecular clouds. When subsequent star formation in the cloud gives rise to the formation of a star cluster, there will be a population of old captured field stars in the cluster together with the new born stars. Also, the captured field stars themselves may provide nuclei for the formation of more massive stars by accretion. These implications are discussed and observational examples are suggested in Sect. 3.

2. Rate of capture of field stars by molecular clouds

The field stars have a distribution of velocities with respect to the local standard of rest. Here, for simplicity, we assume the velocity distribution to be isotropic and Maxwellian. The number of stars per unit volume, $f(u)\,du$, with velocities between u and $u + du$ is given by

$$f(u)\,du = n_* (2/\pi)^{1/2}\, \sigma_*^{-3}\, u^2 \exp(-u^2/2\sigma_*^2)\, du\,, \tag{1}$$

where n_* is the number density of stars and σ_* is their one-dimensional root-mean-square velocity dispersion. Now consider a spherical cloud of mass M_c and radius R_c moving with a velocity v_c with respect to the local standard of rest. Let the cloud centre be the centre of the coordinate frame. The rate of gravitational capture of field stars by the cloud is then the number of field stars that enter a sphere of radius $R (= R_c)$ per unit time, with velocities less than the escape velocity $v_e = (2GM_c/R)^{1/2}$. The number of stars that enter a sphere of radius R, per unit time, with relative velocities between v and $v + dv$ is given by (Eq. (A 5) of Hasegawa, 1976)

$$(dN_*/dt)\,dx = (2\pi)^{1/2} n_* \sigma_* (R^2/x_c) \cdot [\exp\{-(x-x_c)^2\} - \exp\{-(x+x_c)^2\}]\, x^2\, dx\,, \tag{2}$$

where $x = v/2^{1/2}\sigma_*$ and $x_c = v_c/2^{1/2}\sigma_*$.

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Only stars that enter with $v \leqq v_e = (2\,GM_c/R)^{1/2}$ are captured, so the rate of capture of stars is obtained by integrating Eq. (2) between $x=0$ and $x = x_e = v_e/2^{1/2}\sigma_*$. The capture rate is then

$$dN_*/dt = (2\pi)^{1/2}\, n_*\sigma_*\,(R^2/x_c) \int_0^{x_e} \cdot\, [\exp\{-(x-x_c)^2\} - \exp\{-(x+x_c)^2\}]\, x^2\, dx\,. \quad (3)$$

Equation (3) reduces to

$$dN_*/dt = (2\pi)^{1/2}\, n_*\sigma_*\, R^2\, x_e^4 \exp(-x_c^2) \quad (4)$$

provided $x_e^2 \ll 1$ and $2x_c x_e \ll 1$.

Now since $x_e = v_e/2^{1/2}\sigma_* = (GM_c/R\sigma_*^2)^{1/2}$, the rate of capture of field stars can be written as

$$dN_*/dt = (2\pi)^{1/2} n_* (GM_c)^2\, \sigma_*^{-3} \exp(-v_c^2/2\sigma_*^2)\,. \quad (5)$$

It can be noted from Eq. (5) that the capture rate does not depend on R. Thus the capture rate obtained by considering only the stars that enter the cloud surface ($R = R_c$) with velocities less than the escape velocity $v_e = (2GM_c/R_c)^{1/2}$ at the cloud surface is the same as the capture rate obtained by considering a larger radius for the sphere of gravitational influence of the cloud. The effective capture radius is $2\,GM_c/\sigma_*^2$ together with other dimensionless factors appearing in Eq. (5).

The total number of field stars captured by the cloud over a time interval Δt can be written as

$$\Delta N_* = (2\pi)^{1/2}\, n_*\,(GM_c)^2\, \sigma_*^{-3} \exp(-v_c^2/2\sigma_*^2)\,\Delta t\,. \quad (6)$$

We can estimate the number of field stars (and other objects in the field) that can be captured by a molecular cloud over its life Δt by substituting numerical values for the various parameters in Eq. (6). The cloud mass M_c can have any value in the power law mass spectrum, but it is the large mass clouds that would dominate the field star capture process because $\Delta N_* \propto M_c^2$. In fact the cloud mass spectrum is such that most of the cloud mass is in the GMCs with $M_c \geqq 10^5\, M_\odot$. There are $\sim 10^4$ such GMCs in the Galaxy. We use $M_c = 10^5\, M_\odot$ as representative. Molecular cloud complexes with masses much larger than $10^5\, M_\odot$ exist, but they are groups of smaller clouds. The one dimensional cloud-cloud velocity dispersion is $\sim 3\,\mathrm{km\,s^{-1}}$ (Clemens, 1985) so that v_c in Eq. (6) would have a typical value $\sim 5\,\mathrm{km\,s^{-1}}$. Estimates for the mean cloud life time Δt range from $\sim 3\;10^7$ yr to $\sim 2\;10^8$ yr (e.g. Bash, 1979; Blitz and Shu, 1980; Cohen et al., 1980; Solomon and Sanders, 1980; Kwan and Valdes, 1987). We use $\Delta t = 10^8$ yr as a typical value in Eq. (6). For the field stars, the velocity dispersion σ_* and the number density n_* depend on the spectral type of the stars considered (values tabulated in Delhaye, 1965 and Allen, 1973). The velocity dispersion for stars is much larger than that for the clouds. Typically $\sigma_* = 25\,\mathrm{km\,s^{-1}}$, so that $x_c = v_c/2^{1/2}\sigma_* < 1$ and the factor $\exp(-v_c^2/2\sigma_*^2) \simeq 1$. Equation (6) for the number of field stars captured can therefore be written as

$$\Delta N_* \simeq (2\pi)^{1/2}\, n_*\,(GM_c)^2\, \sigma_*^{-3}\,\Delta t \quad (7)$$

and the total mass of stars captured ΔM_* as

$$\Delta M_* \simeq (2\pi)^{1/2}\, \varrho_*\,(GM_c)^2\, \sigma_*^{-3}\,\Delta t\,, \quad (8)$$

where ϱ_* is the mass density of field stars.

The number density of all visible stars (excluding white dwarfs, neutron stars and brown dwarfs) in the Solar neighbourhood $n_* \simeq 0.064\,\mathrm{pc^{-3}}$ while the total mass density in these stars $\varrho_* \simeq 0.044\, M_\odot\,\mathrm{pc^{-3}}$ (Allen, 1973). Therefore, the number of field stars ΔN_* captured by a cloud of mass M_c during its life time Δt can be estimated as

$$\Delta N_* \simeq 2\;10^2\,(n_*/0.064\,\mathrm{pc^{-3}}) \cdot (\sigma_*/25\,\mathrm{km\,s^{-1}})^{-3}\,(M_c/10^5\,M_\odot)^2\,(\Delta t/10^8\,\mathrm{yr})$$

and the total stellar mass captured ΔM_* as

$$\Delta M_* \simeq 1.4\;10^2\,(\varrho_*/0.044\,M_\odot\,\mathrm{pc^{-3}}) \cdot (\sigma_*/25\,\mathrm{km\,s^{-1}})^{-3}\,(M_c/10^5\,M_\odot)^2\,(\Delta t/10^8\,\mathrm{yr})\,M_\odot\,.$$

Thus the number of field stars and stellar mass captured by a massive molecular cloud can be substantial.

The number of field stars and objects of different types captured by a molecular cloud can be estimated separately for each group of objects by using the appropriate values of the parameters n_* and σ_*, corresponding to the different groups of objects, in Eq. (7) which can be expressed as

$$\Delta N_* \simeq 5\;10^2\,(n_*/10^{-2}\,\mathrm{pc^{-3}}) \cdot (\sigma_*/10\,\mathrm{km\,s^{-1}})^{-3}\,(M_c/10^5\,M_\odot)^2\,(\Delta t/10^8\,\mathrm{yr})\,. \quad (9)$$

Table 1 gives the number density n_* and the root mean square velocity dispersion parameter σ_* (from Delhaye, 1965; Allen, 1973) for stars of different types in the Solar neighbourhood. Using these values in Eq. (9), the number ΔN_* of each type of stars captured by a molecular cloud of mass $M_c = 10^5\, M_\odot$ during a time interval $\Delta t = 5\;10^7$ yr has been evaluated and listed in Table 1. The number of stars captured by a cloud of any other mass and a different life time can be estimated by noting that $\Delta N_* \propto M_c^2\,\Delta t$.

Table 1. Number of field stars ΔN_* captured by a molecular cloud of mass $M_c = 10^5\, M_\odot$ and life time $\Delta t = 5\;10^7$ yr

Star type	$\log n_*$ ($\mathrm{pc^{-3}}$)	σ_* ($\mathrm{km\,s^{-1}}$)	ΔN_*
B	−4.0	9	3
A	−3.3	11	9
F	−2.6	17	13
G	−2.2	23	13
K	−2.0	26	14
M	−1.3	29	51
Red giants	−3.2	22	2
White dwarfs	−2.3	37	3

The number density of massive 0 type stars is small and their space distribution far from being uniform. Their life times are short and are therefore found close to their birth places. Also, there are runaway 0 B type stars that have very large velocity dispersions. These objects will not be captured by molecular clouds. The 0 type stars are not included in Table 1. The stars of the earlier spectral types (B, A, F) have relatively small velocity dispersions, but their number densities are low. The late type stars have larger velocity dispersions and also large number densities. The captured stars are mostly main sequence stars of the late spectral types, but the number of early type stars, evolved red giants and white dwarfs are also significant. In fact, among the captured stars, the proportion of the early type stars is much higher than it is among the field stars. The mass distribution function for the captured stars is rather flat compared to the field star mass distribution function.

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3. Discussion

The field stars thus captured by a molecular cloud are gravitationally bound to it. Subsequent star formation in the cloud gives rise to a star cluster. The types of stars (low mass or high mass) and the efficiency of their formation in molecular clouds depend on a number of factor still not well understood, but typically only a few percent of the cloud mass is converted into stellar mass (e.g. Elmegreen, 1985) so that the captured field stars can represent a significant fraction of the contents of the cluster. The newly formed cluster would contain two populations of objects: young stars born from the cloud and old stars and objects captured from the field. This can have interesting consequences for observations of young star clusters.

(i) Presence of very low mass stars on the main sequence. The colour-magnitude diagram for a cluster containing only the new-born stars would exhibit the main sequence turn off point and the main sequence turn on point at positions corresponding to the cluster age. The cluster main sequence stars should occupy positions on the main sequence only between these two points. No low mass stars are expected to be on the main sequence to the lower right of the main sequence turn on point. For a cluster of young age such low mass stars should still be pre-main sequence objects and occupy positions far above the main sequence. Now, as found in Sect. 2, a relatively large number of low mass main sequence field stars are captured by the cloud. These stars would occupy positions on the main sequence in the colour-magnitude diagram for the cluster even to the lower right of the main sequence turn on point, otherwise considered anomalous. Extending cluster star photometry to faint limits (corresponding to the low mass stars) should show up this phenomenon. In the Pleiades cluster (age $\sim 6\ 10^7$ yr, Harris, 1976; Patenaude, 1978), stars with masses as low as $\sim 0.3\ M_\odot$ are on the main sequence (Stauffer, 1982; Van Leeuwen, 1985) while the main sequence turn on point is at $\sim 0.8\ M_\odot$. The pre-main sequence contraction time (the time required to reach the main sequence) for stars of such low mass is $\gtrsim 3\ 10^8$ yr (Grossman et al., 1974), much in excess of the cluster age. The presence of these low mass stars on the main sequence could be explained if they were stars captured from the field by the molecular cloud that produced the Pleiades cluster.

(ii) Presence of evolved objects in young clusters. A massive molecular cloud can also capture evolved objects (like red giants, white dwarfs) from the field. In the young star cluster that results from the molecular cloud, the presence of such evolved objects would otherwise be considered anomalous. In the colour-magnitude diagram for the cluster, the captured field red giants would occupy positions above the main sequence, but would generally be fainter than the main sequence turn off stars because the progenitors of the field red giants are pre-dominantly low mass stars. The distance moduli and proper motions of the captured stars would be similar to those for the cluster member stars. The presence of red stars occupying anomalous positions on the colour-magnitude diagrams for a number of young open clusters [e.g. NGC 2232, 2264, 2451, 2546, 2548 (Claria, 1985) and NGC 6530 (Sagar and Joshi, 1978)] but consistent with cluster membership may be explained if these were stars captured from the field.

A molecular cloud can capture white dwarfs from the field. Also red giants captured from the field can evolve into white dwarfs. While the presence of white dwarfs in young clusters (e.g. NGC 2451; Koester and Reimers, 1985) is generally taken to support the view that their progenitors were cluster stars more massive than the main-sequence turn off stars, it is possible (especially for the cool white dwarfs) in some cases that these are stars captured from the field.

(iii) The captured stars would accrete matter from the molecular cloud. The rate of accretion of matter $\dot{M} \simeq \pi R_a^2 v \varrho$. where $R_a = (2GM_*/v^2)$ is the accretion radius, v is the velocity of the star of mass M_* relative to the cloud and ϱ is the density of the cloud. The accretion rate depends sensitively on the relative velocity:

$$\dot{M} \simeq 3\ 10^{-9}\,(M_*/M_\odot)^2\,(v/\mathrm{km\,s^{-1}})^{-3}\,(\varrho/10^{-21}\,\mathrm{g\,cm^{-3}})\,M_\odot\,\mathrm{yr}^{-1}.$$

Significant amount of the cloud material can be accreted by a captured star over a time scale $\sim 10^8$ yr for low relative velocities $\lesssim 1$ km s^{-1}. Such stars can act as nuclei for the formation of more massive stars by accretion. However, since the relative number of stars with low velocities is small, this will not be a commonplace phenomenon. For larger relative velocities, the amount of accreted material is less, but still substantial to cause observable effects; for example, the formation of circumstellar shells or discs around the stars.

4. Conclusions

In this paper we have considered the capture of field stars by interstellar clouds. The more massive molecular clouds, during their long life times, can capture a significant number of stars from the field. We have estimated the number of stars of different types that can be captured by a typical giant molecular cloud. Star clusters that form from the clouds contain the captured field stars in addition to the newly born stars. The existence of stars occupying anomalous positions on the colour-magnitude diagrams for the clusters can be explained if they were captured from the field. The very low mass stars on the main sequence of the Pleiades cluster and evolved stars in some other young clusters may be examples of such objects that were captured from the field by molecular clouds.

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