POSSIBLE INFLUENCE OF COMETS ON THE CHEMICAL EVOLUTION OF THE GALAXY

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Abstract. It has been suggested by Cameron that a cloud of comets containing a mass of condensable elements, comparable to the mass of such elements in the sun, formed on the outskirts of the solar system. If the formation of such comet clouds is a general feature of star formation, they constitute a significant sink of elements heavier than helium. It is shown here that this process provides a possible explanation for the very slow rate at which the mean metal abundance of disk stars has increased during the lifetime of the Galaxy.

1. Introduction

It has been proposed by Cameron (1973) that a mass of cometary material, possibly comparable to the mass of condensable elements in a solar mass of interstellar gas, condensed in satellite gaseous nebulae on the outskirts of the solar system during its formation. The purpose of this paper is to show that, if such a process is a general feature of star formation, the resulting sink of heavy elements may have a profound effect on chemical evolution of the Galaxy. In particular, the following long-standing puzzle may find a plausible solution.

The mean metal abundance of the oldest stars in the disk population of the solar neighborhood is no less than about half that of the youngest stars (e.g., Hearnshaw, 1972). Yet the most straightforward arguments predict that the abundance of heavy elements (Z) of the interstellar gas should be doubling on a time scale of about $3 \times 10^9$ yr: the present birthrate is approximately $2\%$ of the total mass density (in a column perpendicular to the Galactic plane) per $10^9$ yr, interstellar gas comprises about $5\%$ of that density, and nucleosynthesis theory predicts that about $2\%$ of the mass formed into stars is returned promptly as new heavy elements (e.g. Talbot and Arnett, 1973a); thus Z is expected to increase by about $0.008$ per $10^9$ yr, which is a significant fraction of its present value ($\sim 0.025$).

Several solutions to this problem have been suggested previously. The various hypotheses include formation of black-hole remnants by massive stars, so that their newly-synthesized heavy elements are not ejected (Truran and Cameron, 1971), continual infall of metal-poor gas which dilutes the stellar enrichment (Larson, 1972; Quirk and
Tinsley, 1973; Biermann and Tinsley, 1974), and enhancement of star formation in regions of above-average $Z$ in a chemically inhomogeneous interstellar medium (Talbot and Arnett, 1973b). Here we present another alternative.

2. The Formation of Comets

The mass of comets in the solar system is very difficult to determine directly. Statistics of observed cometary orbits yield estimates of the mass present in the Oort cloud, at radii of the order of $10^5$ AU where perturbations by passing stars are most effective in sending new comets into the solar system. Such estimates range from about 1 Earth mass (if it is assumed that the cometary orbits are highly eccentric with a relatively small range of parameters) to about $10^3$ Earth masses (if the orbital parameters are more or less uniformly distributed) (Opik, 1973). However, the radial distribution of comets in the Oort cloud is completely unknown, and there could be in addition to this mass near $10^5$ AU, large amounts of cometary mass stored at smaller distances, whose presence would not be revealed because stellar perturbations would affect them relatively little. If comets were originally made in the vicinity of Jupiter (Oort, 1950; Opik, 1973), the process of planetary perturbations will tend to eject much more mass from the original solar system than is presently stored in the Oort cloud. On the other hand, one of us (Cameron, 1973) has recently suggested that comets were formed in gaseous disks in orbit about the original primitive solar nebula. There may have been several such disks, each starting with several tenths of a solar mass of material of interstellar composition and they are ideal environments for the formation of comets. The total mass of these disks could well exceed one solar mass. This indicates that, when the solar system was formed, as much as one solar mass of gas may lose all of its condensable elements in the formation of comets.

3. Effects on Chemical Evolution

The approximate analytical treatment given in this section shows how importantly chemical evolution may be affected if the above process of comet formation occurs generally when stars are formed.

Consider the mass of gas, $M_g$ in a system, and its abundance, $Z$, of heavy elements. In unit time, the gas is depleted by formation of a total mass $\psi(t)$ of stars, while a mass $R(t)\psi(t)$ is ejected from dying stars back into the interstellar medium. In the ejected material, there is a mass $R_z(t)\psi(t)$ of heavy elements that had been in the stars since birth, and a mass $P(t)\psi(t)$ of newly synthesized heavy elements. The fractions $R$, $R_z$, and $P$ depend on time, since finite stellar lifetimes cause the past history of the birthrate and $Z$ to affect the ejection rates. However, numerical models (e.g. Talbot and Arnett, 1971) show that, provided the initial mass function (IMF) for star formation is constant, it is a good approximation to treat $R$ and $P$ as constants and $R_z$ as $Z(t)R$. The present local IMF and nucleosynthesis theory lead to estimated values