A NEW SCENARIO FOR THE FORMATION OF GLOBULAR CLUSTERS AND THEIR PECULIARITIES

Alberto Di Fazio
Osservatorio Astronomico, Roma, Italy

Alvio Renzini+
Osservatorio Astronomico, Bologna, Italy

Globular clusters in galaxies still challenge astronomers to find a satisfactory explanation for a number of their properties, namely: (i) their very formation; (ii) the origin of their heavy elements; (iii) the trend of their metallicity with distance from the centre of the parent galaxy; (iv) the apparent correlation of their average metallicity with the mass of the galaxy with which they are associated; and, (v) the need of a "second parameter" (age? helium? [CNO/Fe]?) to explain the variety of morphologies of their colour-magnitude diagrams. Dwarf spheroidal galaxies pose similar problems, to an even more puzzling degree. It is clear that an understanding of the above topics is practically the same as the understanding of the very early evolution of galaxies. Any model for the formation and early evolution of galaxies should necessarily be tested whether or not the predicted properties of the associated globular cluster family are in agreement with the observational constraints. Conversely, any attempt to account for the characteristics of globular clusters would be blind without the support of detailed protogalactic models.

A great deal of insight into these problems may be provided by recently computed fully hydrodynamical models of collapsing protogalaxies, which take into account both star formation and chemical pollution of the ISM (Di Fazio, Vagnetti and Wilson, 1979). According to these models, a strong shock in the gas component develops as a result of the core bounce following collapse. The ultimate effect of the shock is the ejection of about 20% of the original mass of the galaxy. In the meantime, a significant fraction of stars formed during the collapse is accelerated to high velocities through the interaction with the rapidly changing gravitational potential during core bounce. Actually many of these stars are accelerated to velocities

+Visiting Professor, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064.

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exceeding the escape velocity, and leave the galaxy unless they first explode as supernovae. According to the models the "wave" of high velocity stars precedes the shock in the gas component, polluting the infalling gas with "metals" prior to its interaction with the radially outgoing shock wave, and establishing a radial gradient in metal abundance.

Shock waves in the ISM have been widely considered in the context of star formation, and we suggest that the formation of globular clusters may actually be triggered by the shock wave in the gas component through the strong compression that protogalactic clouds will suffer at its passage. Quite naturally the models also predict significant variations of [CNO/Fe] from place to place in the protogalaxy, as a result of the high relative motions of the stellar component with respect to the gas component. In fact, among the high velocity stars emerging from the central regions, the more massive ones explode closer to the centre, while the less massive ones explode further out. Therefore, the mass spectrum of exploding supernovae depends upon the galactocentric distance and a variable [CNO/Fe] is produced.

Finally, we speculate that the same scenario could also explain the formation and characteristics of dwarf spheroidal galaxies if one assumes that low density clouds were still falling towards the galaxy. Similarly to what we suggest for globular clusters, such clouds would first be polluted by supernovae produced by the stars ejected by the central galaxy, and would then be turned into stars by the later arrival of the gas ejected at high velocity by the radial shock wave.

The main conclusions of this research are: (i) the chemical and dynamical evolution of protogalaxies are so intimately connected that an attempt to decouple them is probably bound to failure; (ii) strong shock waves in the gas component are likely to develop in the early phases of evolution of protogalaxies, even in absence of collisions with "mergers"; (iii) such strong shock waves could be responsible for the formation of globular clusters and perhaps also for the star formation in dwarf spheroidal galaxies; (iv) a gradient in [CNO/Fe] is likely to be produced in galactic halos during the early evolutionary phases of protogalaxies, and therefore [CNO/Fe] appears to be the best candidate for the "Second Parameter".

REFERENCE

Di Fazio, A., Vagnetti, F., and Wilson, J.R.: 1979 (in press).

DISCUSSION

VAN DEN BERGH: One might imagine that in a collapsing giant galaxy the shocks would be much stronger than in collapsing dwarf galaxies. Might this not affect the mass spectrum of clusters?

RENZINI: That's quite a possibility. On the other hand, Di Fazio and collaborators have computed a model for a more massive protogalaxy ($\sim 10^{13}$ $M_\odot$) in which star formation was neglected. They find that the shock develops at a later stage, when the central density is higher. As radiative losses are more important under such conditions, it may well be that there is a self regulating mechanism that causes the strength of the shock to be relatively insensitive to the initial conditions. But, really, one has to wait for more calculations to establish this point, and unfortunately such calculations are very expensive.

WALLERSTEIN: I would just say that this is a very valuable suggestion. In the past there's always been this problem of how do you ever get globular cluster stars which have practically no metals. Perhaps we talk about an extinct generation of globular cluster stars, but at zero metals how could they have ever formed? You have a much better chance to get the first generation of stars to form where the density will naturally be suddenly very high, such as during the initial collapse at the center of the galaxy. Then, when you have these stars running out ahead, polluting the scene in front of the shock, you will have at least some metals available to assist in the radiative cooling and so on, so it helps formation of stars in the globular clusters.

KING: Do you think that this scenario would go approximately the same if you had a rotating system that collapsed into a disk rather than a point?

RENZINI: Well, I would say that at least for those galaxies having a substantial bulge-halo component it should be more or less the same. For irregular galaxies or galaxies without the nucleus, I doubt it.

RACINE: I'm not sure I understand why this would lead to the formation of globular clusters rather than individual stars.

RENZINI: Oh, that's a problem that one also has to address numerically. Woodward (1978, Ann. Rev. Astron. Astrophys. 16, 555) has recently computed numerical simulations of what happens when a cloud is hit by a shock wave. In his calculations the adopted parameters are those pertinent to the case of a typical molecular cloud and the shock is that associated with a spiral arm. He finds that the cloud becomes fragmented, but there are substantial fragments which are squeezed to very high densities. For the case of the formation of globular clusters, it would be very important to repeat the sort of calculations Woodward did, chosing parameters which are appropriate for the situation which is described here. Say, cloud masses of the order of 10^6-10^7 $M_\odot$, and a shock strength of the order of that found by Di Fazio et al.

HARWARDEN: How important is the symmetry of your model for the development of the shock wave? It seems to me that the model might be applicable to those cases where galaxies are accreting large amounts of material from neighbouring galaxies, but then the situation would be that the accretion process would not be completely symmetric. In this case would you expect such a shock to develop?

RENZINI: There are essentially two families of models for the formation of galaxies. In the first family (to which the present model belongs) a galaxy is formed by the collapse of a unique protogalactic cloud; and then you have the other family of models based on mergers. You may have also hybrid models in which an initial collapse is followed by the accretion of other fragments. Anyway, apart from the shock originating in the overall collapse, in the accretion process you may well develop strong shocks. They could also trigger the formation of globular clusters in the same way, which may also produce streams of high velocity stars that will, eventually, explode in different places in the protogalaxy, according to their mass. So I think that a simple minded model for the formation of globular clusters, in which a cluster is formed by the collapse of an isolated cloud of 10^5 to $10^6 M_\odot$, is not viable at all.

SCHOMMER: Do you have any insight on how you could form dwarf spheroidals and globulars, at about the same galactocentric distance, with apparently about the same mass, but with central densities that differ by 5 or 6 orders of magnitude?

RENZINI: That's a question which is correlated with the problem raised a moment ago by René Racine. When a cloud is shocked by a strong shock wave, depending on the size of the cloud and the strength of the shock, you may have either the overall cloud collapse preceding the fragmentation into protostars, or the fragmentation preceding the collapse. In the first case, you might have something like a globular cluster; in the second, something like a dwarf spheroidal. But, once again, I think that this question cannot be satisfactorily answered until more hydrodynamical models of cloud/shock interactions are developed.

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