HOW DID GLOBULAR CLUSTERS FORM?

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ABSTRACT

It is suggested that there have been at least two physically distinct epochs of massive cluster formation. The first generation of globular clusters may have formed as halo gas was compressed by shocks driven inward by ionization fronts generated during cosmic reionization (Cen 2001) at $z \sim 6$ (Becker et al. 2001). On the other hand a second generation of massive clusters might have been formed at later times by compression, and subsequent collapse, of giant molecular clouds. In some cases this compression may have been triggered by heating of the interstellar medium via collisions between gas-rich disk galaxies. It is also suggested that the present specific globular cluster frequency in galaxies was mainly determined by the peak rate of star creation, with elevated peak rates of star formation per unit area resulting in high present specific globular cluster frequencies (Larsen and Richtler 2000).

Subject headings: globular clusters:general

1. INTRODUCTION

 Twenty years ago Bill Harris and I (Harris & van den Bergh 1981) introduced the specific globular cluster frequency $S$, i.e. the number of clusters per unit of parent galaxy luminosity, which was defined as

$$S = N \times 10^{0.4(M_V + 15)} .$$

Observations of $S$ in a wide variety of parent galaxy types (Harris 1991) showed large variations in the galaxy-to-galaxy specific globular cluster frequency. Major trends were that: (1) $S$ is generally found to be higher in elliptical galaxies than it is for disk galaxies, (2) Many (but not all) central cluster galaxies in galaxy clusters have above-average
S values, (3) among ellipticals S does not appear to depend strongly on parent galaxy luminosity. Notable peculiarities are that (a) M32 contains no globulars [even though 10-20 are expected (van den Bergh 2000, p. 168)], and (2) the Fornax dwarf spheroidalsystem contains an anomalously high number of globulars. It is the purpose of the present note to look in to some of the factors that might have affected the presently observed S values of galaxies.

2. CLUSTER FORMATION DURING MERGERS

van den Bergh (1979) hypothesized that the formation of massive star clusters might have been triggered by strong shocks. Such shocks are expected to be common in starburst galaxies and to be rare in quiescent dwarf galaxies such as IC 1613. Alternatively Ashman & Zepf (2001) have recently suggested that the formation of massive clusters is favored by the high pressure in the interstellar medium (ISM) that is expected to prevail in merging spirals and in starburst galaxies. Ashman & Zepf argue that a high-pressure ISM will compress giant molecular clouds and trigger star and cluster formation within them. Perhaps bound clusters are only produced from the compact cores in such clouds, whereas unbound associations might be formed from their lower density envelopes. Ashman & Zepf propose that the formation of massive clusters by the compression of giant molecular clouds might account for the existence of numerous massive intermediate-age clusters in colliding galaxies such as NGC 4038/4039 (Whitmore et al. 1999). Because the frequency of such mergers (Carlberg et al. 2000) decreases with time, the massive clusters produced by such mergers should be most common at large redshifts.
3. CLUSTER FORMATION AFTER REIONIZATION

An alternative scenario for the formation of massive clusters has recently been proposed by Cen (2001). He points out that reionization of the Universe (Gnedin, Lahav, & Rees 2001; Becker et al. 2001) will drive ionization fronts into the gaseous halos of protogalaxies, resulting in convergent shocks. These shocks will compress the resident gas by factors of $\sim 100$. Cen argues that this compression will lead to fragmentation and to the formation of clusters with masses in the range $10^3 - 10^6 M_\odot$. The clusters so formed might be identified with the first generation of globular clusters. The separation in time between this first generation of globular clusters and later star clusters is particularly clean in the Large Magellanic Cloud (Suntzeff 1992) where all 13 globulars have ages $>10$ Gyr, whereas all but one of the other massive clusters have ages $\leq 3$ Gyr. In our own Milky Way system the situation appears to be more complex, with a generation of halo globular clusters that have below-average ages and masses having formed in the outer halo beyond $R_{gc} = 15$ kpc (van den Bergh 1998). Possibly these outer halo clusters were originally formed in dwarf spheroidal galaxies that were later captured (and tidally destroyed) by the Galaxy. Many of such dwarf spheroidals (van den Bergh 2000, pp. 243 - 264) are known to have undergone major bursts of star formation (during which massive clusters might have formed) a few Gyr after their formation.

4. THE SPECIFIC CLUSTER FREQUENCY

A possible key to understanding the galaxy-to-galaxy variations in the specific globular cluster frequency $S$ is provided by Larsen and Richtler (2000), who have determined the fraction on the ultraviolet light of various galaxies that is emitted by massive [$M > 4000 M_\odot$] and young [age $< 0.5$ Gyr] clusters. These authors find that the fraction of the UV light of galaxies that is emitted by such young massive clusters ranges from $\sim 15\%$ in
the starburst galaxy NGC 3256 to $\sim 0\%$ in the quiescent dwarf IC 1613. The low rate of cluster formation in IC 1613 was first noted by Baade (1963), and was subsequently confirmed by Hodge (1978) and van den Bergh (1979). Figure 1 shows a plot, based on Larsen & Richtler’s data, of the relation between the percentage of the total U light of a galaxy that is emitted by massive young clusters and the mean rate of star formation per unit area. These data show that the fraction of the U light of galaxies that is generated by young clusters is proportional to the rate of star formation per unit area to the power $\sim 1.2$. This result suggests that the present specific cluster frequency in galaxies will, to a large extent, be determined by the peak rate of star formation per unit area during their evolutionary history. The high S values observed in some central galaxies of rich clusters might therefore be due to a high surface density of star formation early in their history. By the same token the observation that elliptical galaxies have higher mean S values than spirals may be interpreted to mean that the peak rate of star formation in E galaxies was higher than that in disk galaxies. This speculation is supported by the observation that the ratio of alpha elements (produced by short-lived SNe II) to iron (formed in longer-lasting SNe Ia) is greater in ellipticals than it is in spiral disks (Wheeler, Sneden, & Truran 1989).

5. SUMMARY AND CONCLUSIONS

It is suggested that there are two families of massive star clusters. The first of these (the classical globular clusters) were produced at high redshift when reionization sent ionization fronts crashing into the gaseous halos of protogalaxies. The formation of the second class of massive clusters was triggered by the squeezing of giant molecular clouds by the hot ISM in which they were embedded, by starbursts initiated by collisions between gas-rich galaxies. The fraction of all star formation that ends up in the form of massive bound star clusters depends critically on the star formation rate per unit area.
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Figure 1. Percentage of ultraviolet light generated by massive young clusters versus rate of star formation in $M_\odot$ yr$^{-1}$ kpc$^{-2}$. The slanted line shows that the fraction of a galaxy’s light emitted by massive young clusters is approximately proportional to the star formation rate per unit area to the power 1.2.
