M31: The Old Stellar Populations

M31 (the Andromeda nebula) is a large highly inclined spiral galaxy about 1.4 times as luminous as our Galaxy. The Milky Way and M31 are the two dominant members of the Local Group of galaxies. The proximity of M31 (about 770 kpc from the Sun) allows its stellar populations to be studied in some detail with the Hubble Space Telescope and large ground-based telescopes. M31 contains all the usual ingredients of a spiral of intermediate (Sb) Hubble type: atomic, molecular and ionized gas, dust, dark matter and stars of all ages. For the study of stellar populations, however, M31's oldest stars are of particular interest, because they show some very significant differences, as a population, from the oldest stars of our Galaxy. Although we do not yet fully understand the reasons for these differences, they surely came about through differences in the processes by which these two large galaxies formed in the early universe.

The bulges of M31 and the Milky Way

In the Milky Way, the disk stars are all younger than about 10 Gyr. The oldest stars (ages up to about 14 Gyr) are found in the spheroidal components of the Galaxy, i.e. the bulge and the very diffuse stellar halo which extends out to at least 100 kpc from the galactic center. These old non-disk components, the bulge and the stellar halo, are often discussed together, although their origin may be quite different.

The structure of the spheroidal component was established by dynamical processes, like the merging of clumps of gas and dark matter and the dynamical instabilities of flat disks, which began at the same time as the oldest stars were forming. So its structure and its old stellar population are intimately related. It is interesting therefore to contrast the structure of the spheroidal components of M31 and the Galaxy before we go on to discuss their stellar content.

The bulge of M31 is relatively large, about 25% of the mass of the disk, while for our Galaxy the corresponding fraction is about 15%. Although these fractions are not so different, the bulges of M31 and our Galaxy are structurally different and typical of large and small bulges respectively. The M31 bulge has the spheroidal shape and the characteristic radial dependence of surface brightness that is seen in most large bulges. Its surface brightness $I(r)$ follows the empirical de Vaucouleurs law $\log I(r) \propto -r^{1/4}$, from a radius of 200 pc out to beyond 20 kpc. From dynamical theory, this $r^{1/4}$ law is associated with the violent relaxation process, in which rapid changes of the gravitational field statistically redistribute the orbital energies and angular momenta of the stars. The stellar system that emerges from this redistribution has the characteristic $r^{1/4}$ surface brightness distribution. Such rapid changes of the gravitational field come about, for example, as clumps of matter interact and merge to form the early bulge. The compression of gas in these same mergers is believed to set off the first bursts of star formation that produced the stars which we now see as the old stellar population of M31.

The bulge of the Milky Way is very different. Its smaller bulge is seen edge-on and shows a box-like shape, with a surface brightness distribution that is exponential with radius. This kind of structure is common for small edge-on bulges. From studying the motions of gas in our Galaxy and in other galaxies with bulges that appear boxy when seen edge-on, we know that these bulges would not appear round and symmetric when viewed from above. The boxy shape is dynamically associated with an asymmetric bar-like structure. These small bar-bulges are believed to form from the disks of the parent galaxies, through the instability of the rotating disk. This is likely to be a much more quiescent process than the violent merging that led to the formation of the larger $r^{1/4}$ bulges.

In comparing the bulges of M31 and the Galaxy, it seems likely that the different dynamical histories of these two bulges would lead to different star formation histories. We might expect the violent early merger processes in M31 to be associated with rapid star formation and chemical evolution, with chemically enriched stars flung out to large distances by the violent dynamical relaxation. On the other hand, in the inner regions of our Galaxy, the star formation and bulge formation appear to have occurred in a more sedate disk-like environment; the bulge itself formed out of the disk, and the stars of the bulge would remain confined to the inner regions of the Galaxy.

The differences between the old stellar populations of M31 and the Galaxy are most readily studied by observing individual stars in globular clusters and in the outer regions of the diffuse stellar populations in these two galaxies.

The halos of M31 and the Galaxy

First we compare the stellar populations of the globular star clusters in M31 and the Galaxy which have now been studied in great detail. Their stellar color–magnitude diagrams (CMDs) and integrated spectra give estimates of chemical abundances and ages. In most of their properties, the clusters in the two galaxies are alike. The stellar populations within individual clusters of the same chemical abundance are similar, as are the distributions of luminosity of the clusters in the two cluster systems and the radial distributions of the clusters within their parent galaxy. The M31 and Galactic globular clusters cover a similar range of chemical abundance, with the outer clusters of M31 being marginally more metal-rich than their Galactic counterparts[1].

Despite the similarities in the properties of the globular clusters of M31 and the Galaxy, the metallicity distributions in the diffuse (i.e. non-cluster) stellar halos

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[1] Here 'metal' means all elements heavier than He, and is often denoted generically as Fe: metal abundance is usually expressed in terms of the (Fe/H) ratio as $[\mathrm{Fe/H}] = \log_{10}$ (stellar Fe/H)/(solar Fe/H). For example, a low metal abundance of $[\mathrm{Fe/H}] = -2$ corresponds to 0.01 of the solar value.

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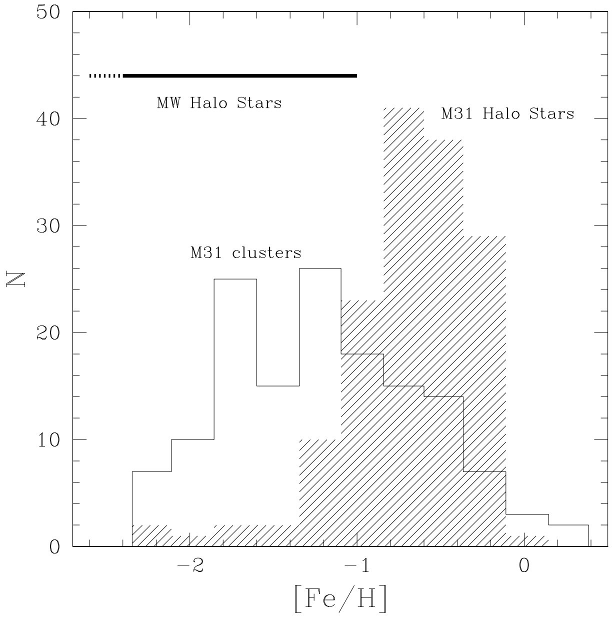

Figure 1. Comparison of metallicity distributions of the M31 halo field stars (hatched) and the M31 globular clusters (adapted from Durrell *et al* (1994)). The bar at the top left indicates the metallicity range of the halo field stars in the Galaxy. The M31 halo stars are much more metal-rich than the Galactic halo stars, although the metallicity distributions for the globular clusters in M31 and in the Galaxy are similar.

of the Galaxy and M31 are strikingly different. For our Galaxy, most halo stars have metallicities [Fe/H] < -1, with a mean of about -1.6. For the outer bulge or halo of M31, CMDs are now available for many fields at distances between about 7 and 40 kpc from the center. All of these studies show that the M31 halo stars cover a very wide range of metallicities, from near-solar down to metallicities [Fe/H] < -2, but the mean metallicity is about -0.6, much higher than for the halo of the Galaxy. This holds true even at the largest radius in M31. Figure 1 shows the marked difference between the metallicity distributions of the stellar halo and the globular clusters of M31. For comparison, the range of metallicities for the Milky Way halo stars is also shown.

Conclusion

What are we to make of the similarities and differences in the stellar populations illustrated in figure 1? The globular clusters in M31 and the Galaxy have similar distributions of metallicity, while the outer stellar halo of M31 is much more metal rich than its Galactic counterpart. These are all old stellar populations, so the origin of the differences will be found in the details of how these galaxies formed, and this is still poorly understood.

Some useful clues are emerging about the nature of the globular clusters. The violent environment of present-day merging galaxies is seen to produce large numbers of young globular-like star clusters. This suggests that the old clusters of our Galaxy and M31 formed in the very early phase of galaxy formation, as clumps of matter were merging together to build the galaxy and the chemical enrichment was proceeding rapidly through massive star formation triggered by the merging.

When we compare the diffuse halos of M31 and the Galaxy, the similarity ends. The two halos are chemically very different, and we must conclude that they formed along quite different paths. At this time, it seems likely that in M31's outer regions we are seeing chemically enriched stars that were scattered out to large radii as part of the violent formation of its $r^{1/4}$ bulge. On the other hand, the halo and bulge of our Galaxy appear to be chemically and dynamically distinct. The Galactic bulge rotates and is relatively metal-rich, like the M31 halo stars in figure 1, while the halo shows no significant rotation and is metal-poor. Following the seminal work of Searle and Zinn (1978), it is now widely believed that the metal-poor stellar halo of our Galaxy is just the debris of small metal-poor satellite galaxies that were accreted and tidally disrupted by our Galaxy. The tidally disrupting Sagittarius dwarf galaxy shows that this process of accretion and halo-building is still going on in our Galaxy.

For more background on M31, see the articles on the ANDROMEDA GALAXY and on the LOCAL GROUP in this encyclopedia.

See also the article on the GALACTIC METAL-POOR HALO.

For current opinions on mergers and the formation and properties of globular clusters, see the articles on GALAXIES: INTERACTIONS AND MERGERS, on GLOBULAR CLUSTERS, on GLOBULAR CLUSTER SYSTEMS IN NORMAL GALAXIES, and on GLOBULAR CLUSTER SYSTEMS IN INTERACTING GALAXIES.

Bibliography

For more details on the chemical abundance distribution in the halo of M31, see

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For the article that started the current view of the formation of the galactic halo, see

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