Andromeda Galaxy

The Andromeda galaxy is the closest SPIRAL GALAXY to the MILKY WAY, just visible to the naked eye on a dark night as a faint smudge of light in the constellation Andromeda. The earliest records of the Andromeda nebula, as it is still often referred to, date back to AD 964, to the 'Book of the Fixed Stars' published by the Persian astronomer AL-SÛFI. The first European to officially note the Andromeda nebula was Simon Mayer, a German mathematician and astronomer, who was not aware of Al-Sûfi's earlier work. The object is number 31 in the famous MESSIER CATALOG, which dates back to the 18th century, and is therefore often referred to as M31. Another alias for the Andromeda galaxy is NGC 224, since it is number 224 in the NEW GENERAL CATALOG (NGC) compiled by DREYER in 1888. Modern measurements based on Cepheid variables place M31 at a distance of 740 kpc or about 2.4 million light-years. This makes it the closest spiral galaxy to the Milky Way. It is the dominant member of the LOCAL GROUP, and as such it has and continues to fill an important role in studies of galaxy structure, evolution and dynamics, stellar populations, star formation and interstellar medium. Crucial historical developments include HUBBLE's work in the 1920s on the distance to M31, which proved that galaxies outside our own Milky Way exist, and BAADE's work in the 1940s on stellar populations which led to the concepts of old (population II) and young (population I) stars. Many small companion galaxies believed to be associated with M31 have been identified, some only in the past year. They are M32 (low-luminosity elliptical), NGC 147, 185 and 205 (dwarf ellipticals), IC 10 (dwarf irregular), LGS 3 (transition object between dwarf irregular and dwarf spheroidal) and And I, II, III, V and VI (dwarf spheroidals). It is likely that more faint companions remain to be discovered. Figure 1 shows an optical image of the Andromeda galaxy.

Figure 1. Optical image of the Andromeda galaxy and two of its nearby elliptical companions, M32 (below center) and NGC205 (upper right corner). The image measures 100′ on a side, corresponding to 21.5 kpc. Based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital format with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute (ST ScI) under US Government grant NAG W-2166. Copyright © 1994, Association of Universities for Research in Astronomy, Inc. All rights reserved.

Morphology, mass and stellar content

The Andromeda galaxy is a large, early-type spiral of HUBBLE CLASSIFICATION Sb, luminosity class I–II. It has a prominent central bulge of stars with an effective radius of 2 kpc, which extends smoothly into an extended flattened spheroidal component of old stars. As in most spiral galaxies, in addition to the bulge or spheroidal component, there is a thin disk of stars and gas with superposed spiral arm structure. The combined light from the disk stars declines exponentially with distance from the center, as is common for spiral galaxies. The disk scale length is about 5–6 kpc, and M31 is some 50% larger than our Milky Way Galaxy and about twice as luminous. The disk becomes bluer at larger radial distance from the center, and this could be caused by a relatively larger fraction of younger stars there, or a lower abundance of heavy elements. Abundance determinations of oxygen, nitrogen and sulfur in the interstellar medium of M31 do indeed show an overall decrease in these elements compared with hydrogen with increasing radial distance.

The SPIRAL ARM structure of M31 has been difficult to determine, owing to its orientation on the sky. Spiral arm segments show up clearly in the distributions of young massive stars and various interstellar medium tracers such as ionized, neutral and molecular hydrogen gas, and dust, but it has not been possible to link the spiral arm segments into an unambiguous grand design spiral structure. A further complication is that the interaction with the close small elliptical companion M32 seems to have distorted the spiral arms as well. The outer stellar and gaseous disks, beyond about 20 kpc, bend out of the principal plane, producing a phenomenon known as warping. Given its bulge size and luminosity, there seems little doubt that M31 is an earlier-type spiral than our Milky Way. For example, the total number of GLOBULAR CLUSTERS, which has been shown to be related to the bulge or spheroid luminosity, is probably between 400 and 500 in M31, almost a factor 3 larger than for the Milky Way. The velocity dispersion of the stars in the bulge of M31 is about 155 km s^{-1}, while for the Milky Way this is 130 km s^{-1}.

From its H I rotational velocity out to 30 kpc radius, one can infer that M31 has a mass of at least 3×10^{11} solar masses, but the total mass will probably be much higher depending on the unknown radial extent of a DARK MATTER halo, a common component in spiral galaxies inferred from the high rotational velocities of gas clouds in the far outer disks. The timing argument for the Local Group implies a mass of a few times 10^{12} solar masses for M31. Given these figures, dark matter must strongly dominate over the mass implied by the visible stars and gas.

The stellar populations in M31 are discussed in the article M31: THE OLD STELLAR POPULATIONS, so a brief summary will suffice here. The bulge and spheroid population is old, although the considerable spread in metal abundances of the stars in the bulge and also the outer halo implies a more complicated formation scenario than a very rapid initial collapse. There is no current star formation in the inner bulge, contrary to the situation in the Milky Way. The properties of the globular clusters of M31 are similar in many ways to those of the Milky Way, i.e. the globular clusters are old, show a range of metal abundances and the same overall correlations between velocity dispersion and luminosity, central and average surface brightness as the Galactic globular clusters. A small number of young massive clusters is found in the disk, at about 10 kpc from the center. Such clusters are common in late-type galaxies, such as M33 and the Magellanic Clouds, but apparently rare in early-type spirals. These could be the progenitors to (low-mass) globular clusters. Interestingly, these objects are mostly concentrated in the tidally disturbed SW spiral arm, and they may be similar to young blue clusters observed in interacting galaxies.

One of the advantages of the close distance of M31 to us is that it enables unique experiments. One of these is the recent attempt to detect MICROLENSING towards M31 bulge stars to constrain the nature of the dark matter. While M31 is too distant to resolve most of its light in individual stars, microlensing can in principle still be detected as a brightening of individual pixels on the detector, if one star of the many contributing to the brightness of that pixel is being lensed by a dark object in M31's halo. Several of these studies are now underway, thereby extending the ongoing microlensing observations of the Galactic bulge and of the Magellanic Clouds.

The central region

The Andromeda galaxy does not contain a particularly active nucleus at its center, but there does appear to be a BLACK HOLE of about 3×10^7 solar masses there. The evidence for this comes from measurements of the stellar velocities close to the center both with the HUBBLE SPACE TELESCOPE and from the ground. The morphology of the central region is quite surprising, with two peaks in the brightness distribution separated by 0.5 arcsec. The currently favored interpretation is that this apparent double nucleus is actually caused by a single eccentric disk of stars orbiting the black hole. The brighter of the two 'nuclei' would then be caused by stars piling up near the apocenter of the eccentric disk, where their speeds are low, while the fainter 'nucleus' would be due to the increase in density towards the center.

The lack of strong nuclear activity associated with the black hole could be due to the general lack of interstellar medium in the M31 bulge. No H I or CO has been detected within 1 kpc from the center, although there are some dust clouds seen in projection against the bright stellar continuum. A faint diffuse 'spiral disk' is seen in ionized gas, with a radial extent of about 500 pc, but it only contains a small amount of mass, perhaps as little as 1500 solar masses total. This gas possibly originates from mass lost by low-mass evolving stars in the form of stellar winds. The lack of activity also manifests itself in the weak level of radio continuum emission, about a factor of 10 less than for the Galactic center.

Star formation and interstellar medium

As the closest nearby spiral, M31 has been a prime target for exploring the properties of various gaseous phases of the interstellar medium and massive stars, and the connections between them. The spatial distribution of all these components, be they neutral or ionized gas, dust or OB stars, is very similar: there is a general lack of gas and young stars in the inner several kpc, some gas and star formation in spiral arms 3–5 kpc from the center, strong concentrations in an annulus between 8 and 12 kpc and modest concentrations in arms out to 15 kpc. Beyond this, the H I disk continues to show spiral structure out to 25 kpc or so, with weak ongoing STAR FORMATION in selected regions. Star formation rates can be estimated from the distribution of ionized gas (H II regions and diffuse ionized gas), which requires hot, luminous, hence massive and young, stars to ionize it, far-infrared emission radio continuum emission and UV light. In addition, the proximity of M31 allows detection of individual OB stars and of evolved tracers of young massive stars such as WOLF–RAYET STARS and LUMINOUS BLUE VARIABLES. All these tracers indicate that the overall level of star formation activity in M31 is quite low, about $\approx$ 0.3–0.5 solar masses yr^{-1}, compared with the Milky Way and other spirals, such as M33. In addition, M31's largest star-forming complexes appear modest compared with those found in other galaxies.

The mass of atomic hydrogen gas is about 4×10^9 solar masses, while that of molecular hydrogen is more than a factor of 10 lower; the uncertainty in the conversion factor of the CO line flux to molecular gas mass makes the latter estimate rather inaccurate, but the low molecular hydrogen surface density is consistent with the overall low rate of star formation in M31. There is some evidence for the presence of very cold molecular gas in M31, which might have further implications for the total molecular gas mass. M31 was one of the first external spirals where a widespread distribution of ionized gas outside of traditional H II regions was detected. This diffuse ionized gas, also referred to as warm ionized medium, is the dominant component, in terms of mass and spatial extent, of ionized gas in galaxies. It requires a large amount of energy to remain ionized, and its widespread distribution implies that the morphology of the interstellar medium has to be very porous, or else the ultraviolet photons from OB stars could not travel far from their origins before being absorbed.

Information on COSMIC RAYS and the magnetic field distribution in M31 has been obtained from detailed radio continuum observations at several frequencies. The radio continuum is strongly dominated by non-thermal synchrotron emission, stemming from highly relativistic electrons spiraling in a magnetic field. Information on field strength and direction can be inferred from the intensity of the emission, the polarization vectors and the rotation measures observed towards extragalactic background sources. The large-scale magnetic field extends from 5 kpc interior to the star formation annulus to as far as 25 kpc from the center. The main field organization is toroidal, aligned along the annulus, with some evidence for a poloidal component extending into the halo. The structure of the field appears to be that expected for an even-mode DYNAMO.

Outlook for the future

There is no question that the Andromeda galaxy will continue to play a central role in future investigations of the morphology and evolution of galaxies, just as it has in the past. With the next generation of telescopes, on the ground and in space, we can expect new results in many areas, such as microlensing studies, high-resolution maps of all the interstellar medium components, abundance measurements in individual stars and further unraveling of the star formation history of M31's disk and bulge.

Bibliography

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