lung) and in this case it indicates that the gas has a temperature of about 10^4 K. Galaxies are mapped at various radio continuum wavelengths, although because of the longer wavelengths the power to see detail or ANGULAR RESOLUTION is less good than at optical wavelengths.

By observation of spectral lines at specific radio wavelengths, a few of the most abundant galactic interstellar molecules – carbon monoxide (CO), hydroxyl (OH), water (H_2O) and formaldehyde (H_2CO) – have been detected, but only in a handful of nearby galaxies. Similarly, radio spectral lines from atoms in H II regions have been detected in a few galaxies. Only one radio spectral line, the 21-cm line of atomic hydrogen, is easily observed in other galaxies. Therefore, it is important for mapping galaxies, just as it is for mapping our own Galaxy (page 186). Of course, viewing a galaxy from outside, we can see more clearly the spiral arm pattern and the general distribution of hydrogen gas. Several hundred galaxies have been studied using the 21–cm line, the objects being to determine the amount of hydrogen present (or to establish an upper limit), to map its detailed distribution and, using Doppler shifts, to determine galaxian rotation. Rotation can lead to a value for the mass of the galaxy.

The value deduced for the mass of hydrogen as a fraction of the mass of the galaxy is proportional to the value assumed for the distance and so depends on the value of Hubble's constant. This introduces uncertainty, but at least the data show clearly a very strong increase of hydrogen content from early to late type. In contrast, the average density of hydrogen gas is found to depend weakly if at all on galaxy type; thus in the later-type galaxies the gas is distributed within a larger volume.

The contour lines showing the strength of 21-cm radiation follow the optical spiral arms quite closely. In most cases, the hydrogen is detected in the plane of the galaxy much further out than any optical emission; indeed, often it extends twice as far out, as in our Galaxy. In many cases, the outer parts of the plane of this hydrogen distribution are warped. There is notably little hydrogen gas in the centre of a spiral galaxy, where it is brightest optically; this is consistent with the distribution of other Population I material, and is also found in our Galaxy.

Elliptical galaxies

There is little optical evidence for interstellar matter in normal elliptical galaxies, although emission lines from ionized gas are observed in the nuclei of some giant ellipticals. Most ellipticals are not radio sources either, but a few contain very strong radio sources and are classified among the **radio galaxies**. These rare elliptical galaxies are a type of active galaxy; their radio emission is not thermal.

The first detection of 21-cm emission from an elliptical galaxy came only in 1977 when two groups, in the United States and in France, found approximately 0·1 per cent hydrogen gas in the active galaxy NGC 4278. Since then, a few other detections have been made, but for most galaxies studied an upper limit in the range 0·1–0·01 per cent is all that can be established. Similar upper limits have been set for galactic globular clusters.

These upper limits are unexpectedly low, because Population II galaxies and globular clusters contain many highly-evolved stars which must have lost substantial mass by ejecting material into interstellar space within the galaxy. To account for the upper limits observed for both neutral and ionized gas we must suppose that these galaxies themselves are losing material, in what could be called a **galaxian wind**.

Structures and dimensions of galaxies

Elliptical galaxies appear as ellipses in the sky. Their true three-dimensional shapes are presumed to be oblate spheroids with flattening produced by rotation, although recent measurements of rotational velocities suggest that this could be an oversimplified picture. Since we see galaxies orientated at random, the relative numbers with different shapes can be deduced statistically. It is found that there are not many truly spherical galaxies. Also, there are no elliptical galaxies with true ellipticity flatter than 0·7: flatter galaxies have discs and nuclei.

Studies of the distribution of luminosity in elliptical galaxies show an increase of brightness towards the centre, indicating an increase in the density of stars there. Moreover, as the intensity falls off faster near the outer boundary, the size of ellipticals can be determined relatively accurately.

For a spiral galaxy, the basic structure is a nucleus plus a disc containing spiral arms. The spiral arms contain Population I material, while Population II material is found in the nucleus and distributed evenly over the disc; the relative size of the nucleus and the strength and degree of openness of the arms are, as we have seen, classification parameters. Within the nucleus there is a distribution of luminosity similar to that in an elliptical galaxy. The disc, averaged round in angle to smooth out the spiral structure, is bright beside the nucleus and becomes fainter quite rapidly with radius, but there is no sharp boundary. A longer photographic exposure reveals material farther out, while in the 21-cm line, hydrogen gas is often seen at twice the radius detectable optically. It is not easy, therefore, to determine, the full dimensions of spiral galaxies. Further, it has been suggested that the dynamical stability of a rotating disc system requires a massive outer halo, so far unobserved, although recent observations do indicate that in our own case this may exist. The discovery that the Galaxy (and others) have coronae (page 172) is further evidence of material occurring outside main discs of galaxies.

Although in barred spirals the bar is prominent optically, it does not, in fact, represent a large distortion from circular symmetry.

Galaxian diameters range from 1 kpc or less for dwarf ellipticals up to 50 kpc or more for the brightest cD galaxies seen in rich clusters. The largest galaxies have absolute magnitude about −23 (if Hubble's constant H_0 = 55 km per s per Mpc) corresponding to a luminosity of about 10^{11} Suns.