15. The Interstellar Medium

Although most of the mass of the Milky Way Galaxy is condensed into stars, interstellar space is not completely empty. It contains gas and dust in the form both of individual clouds and of a diffuse medium. Interstellar space typically contains about one gas atom per cubic centimetre and 100 dust particles per cubic kilometre.

Altogether, about 10% of the mass of the Milky Way consists of interstellar gas. Since the gas is strongly concentrated in the galactic plane and the spiral arms, in these regions there are many places where the quantities of stars and interstellar matter are about equal. The dust (a better name would be "smoke", since the particle sizes are much smaller than in terrestrial dust) constitutes about one percent of the gas. High-energy cosmic ray particles are mixed with the gas and dust. There is also a weak, but still very important, galactic magnetic field.

At present the most important observations of the interstellar medium are made at radio and infrared wavelengths, since the peak of the emission often lies at these wavelengths. But many forms of interstellar matter (such as solid bodies with diameters larger than 1 mm) would be almost impossible to detect on the basis of their emission or absorption. In principle, the mass of these forms of matter might be larger than the observed mass of all other forms put together. However, an upper limit on the total mass of interstellar matter, regardless of its form, can be derived on the basis of its gravitational effects. This is the Oort limit. The galactic gravitational field is determined by the distribution of matter. By observing the motions of stars perpendicular to the galactic plane, the vertical gravitational force and hence the amount of mass in the galactic plane can be determined. The result is that the local density within 1 kpc of the Sun is \((7.3-10.0) \times 10^{-21} \text{ kg m}^{-3}\). The density of known stars is \((5.9-6.7) \times 10^{-21} \text{ kg m}^{-3}\) and that of known interstellar matter about \(1.7 \times 10^{-21} \text{ kg m}^{-3}\). Thus there is very little room for unknown forms of mass in the solar neighbourhood. However, the limit concerns only the dark matter concentrated in the galactic plane. There are indications that the Milky Way is surrounded by a spherical halo of dark matter (Chap. 17).

15.1 Interstellar Dust

The first clear evidence for the existence of interstellar dust was obtained around 1930. Before that, it had been generally thought that space is completely transparent and that light can propagate indefinitely without extinction.

In 1930 Robert Trumpler published his study of the space distribution of the open clusters. The absolute magnitudes \(M\) of the brightest stars could be estimated on the basis of the spectral type. Thus the distance \(r\) to the clusters could be calculated from the observed apparent magnitudes \(m\) of the bright stars:

\[
m - M = 5 \log \frac{r}{10 \text{ pc}}.
\]  
(15.1)

Trumpler also studied the diameters of the clusters. The linear diameter \(D\) is obtained from the apparent angular diameter \(d\) by means of the formula

\[
D = dr,
\]  
(15.2)

where \(r\) is the distance of the cluster.

It caught Trumpler’s attention that the more distant clusters appeared to be systematically larger than the nearer ones (Fig. 15.1). Since this could hardly be true, the distances of the more distant clusters must have been overestimated. Trumpler concluded that space is not completely transparent, but that the light of a star is dimmed by some intervening material. To take this into account, (15.1) has to be replaced with

\[
m - M = 5 \log \frac{r}{10 \text{ pc}} + A,
\]  
(15.3)

where \(A \geq 0\) is the extinction in magnitudes due to the intervening medium. If the opacity of the medium is assumed to be the same at all distances and in all directions, \(A\) can be written

\[
A = ar,
\]  
(15.4)

where \(a\) is a constant. Trumpler obtained for the average value of \(a\) in the galactic plane, \(a_{pg} = 0.79 \text{ mag/kpc}\), in photographic magnitudes. At present, a value of 2 mag/kpc is used for the average extinction. Thus the extinction over a 5 kpc path is already 10 magnitudes.
The increase of the diameter with distance is not a real phenomenon, but an effect of interstellar extinction, which was discovered in this way:

Extinction due to dust varies strongly with direction. For example, visible light from the galactic centre (distance 8–9 kpc) is dimmed by 30 magnitudes. Therefore the galactic centre cannot be observed at optical wavelengths.

Extinction is due to dust grains that have diameters near the wavelength of the light. Such particles scatter light extremely efficiently. Gas can also cause extinction by scattering, but its scattering efficiency per unit mass is much smaller. The total amount of gas allowed by the Oort limit is so small that scattering by gas is negligible in interstellar space. (This is in contrast with the Earth’s atmosphere, where air molecules make a significant contribution to the total extinction).

Interstellar particles can cause extinction in two ways:

1. In absorption the radiant energy is transformed into heat, which is then re-radiated at infrared wavelengths corresponding to the temperature of the dust particles.

2. In scattering the direction of light propagation is changed, leading to a reduced intensity in the original direction of propagation.

An expression for interstellar extinction will now be derived. The size, index of refraction and number density of the particles are assumed to be known. For simplicity we shall assume that all particles are spheres with the same radius \( a \) and the geometrical cross section \( \pi a^2 \). The true extinction cross section of the particles \( C_{\text{ext}} \) will be

\[
C_{\text{ext}} = Q_{\text{ext}} \pi a^2,
\]  

where \( Q_{\text{ext}} \) is the extinction efficiency factor.

Let us consider a volume element with length \( dl \) and cross section \( dA \), normal to the direction of propagation (Fig. 15.2). It is assumed that the particles inside the element do not shadow each other. If the particle density is \( n \), there are \( n \, dl \, dA \) particles in the volume element the total area covered by the particles is \( n \, dA \, dl \, C_{\text{ext}} \). Thus the fractional decrease in intensity over the distance \( dl \) is

\[
\frac{dI}{I} = -n \, dA \, dl \, C_{\text{ext}} / dA = -n \, C_{\text{ext}} \, dl
\]