by about 3×10^9 years ago, and since then impacts have occurred at a lower rate. There are also some indications of fluctuations in this lower rate, possibly due to the break-up of larger bodies to give showers of meteoroids, or else by planets pulling groups of bodies into collision orbits.

There are suggestions that the planetary atmospheres could have been formed by later accretion of volatile materials, and that this could account for some of the differences between Earth and Venus in particular. There are three methods by which later accretion of atmospheric materials could take place: condensation from a hot solar nebula; capture of a significant amount of the solar wind; and the impact of volatile-rich comets and planetesimals. Although there are certain points which favour the first two as subsidiary causes of the Venus:Earth difference, isotopic ratios do not suggest that the atmospheres of these two planets formed from solar-type material. Although the impact of 'cometary' bodies is certainly likely to have occurred, there is no real evidence that it was the sole source of atmospheric materials, so that the outgasing theory remains the most likely candidate for the time being.

The early atmospheres of Earth, Venus and Mars are likely to have been largely composed of carbon dioxide, carbon monoxide, nitrogen and some hydrogen, with some additional trace gases. It appears probable that liquid water has been present at some time on both Venus and Mars, but the former planet has evolved to its present atmospheric state largely because of the temperature conditions, while Mars has lost most of its early atmosphere to space and by chemical reactions with the surface materials. On Earth, plants have made a considerable contribution towards the amount of free oxygen which is now present in the atmosphere.

The origin of comets remains uncertain but there are two principal classes of theory which might explain their occurrence. In the first, comets formed from small cloud fragments in orbit about the nebula, doing so at about the same time as the planets were formed.

Perturbations by nearby stars are probably responsible for the injection of comets into the inner Solar System. The other suggestion is that comets were formed at a later date either by the gravitational pull of the Sun as it encountered a concentration of dust and gas, or by compression in front of an advancing galactic spiral arm. Either class of theory could account for the observed distribution of cometary orbits.

Other planetary systems

Although it has been possible to gain a reasonable idea of the way in which the Solar System was formed, it is difficult to obtain direct evidence for the existence of other planetary systems. However, there are various indications that such systems do exist and have been observed.

The nebular clouds from which stars form rotate slowly, but this rotation speeds up as they contract so that ANGULAR MOMENTUM is conserved; protostars will therefore be rotating much more rapidly. Spectroscopic observations show that there is a tendency for the earlier spectral classes O to about F4 (see page 48) to remain fast rotators. This had been taken to indicate that stars of later spectral classes (F5 to M) had transferred most of their angular momentum to companion bodies where most of the energy is expressed in orbital motion. However, with greater realization that even stars of late spectral classes may still emit intense stellar winds in the process of their formation, and thus could lose much of their initial angular momentum, this argument has lost much of its validity. It is quite possible that even in the case of the Solar System, where the massive planet Jupiter possesses about 98 per cent of the total angular momentum, the Sun, with its low rotational velocity of about 2 km per s at the surface, may have lost most of its angular momentum through an intense stellar wind.

The minimum mass which can give rise to thermonuclear fusion and produce a true star is about $0{\cdot}06\ M_\odot$. Between this and about $0{\cdot}01\ M_\odot$, objects will be luminous for about 10^9 years due to the release of gravitational energy as they contract, but after this time they will become non-luminous bodies or dark stars (sometimes called black dwarfs). Any mass smaller than about $0{\cdot}01\ M_\odot$ may fairly be described as a planet, as it will only radiate away heat at infrared wavelengths – as in the cases of Jupiter and Saturn.

From observations of Doppler shifts caused by the orbital motion of some stars it has proved possible to estimate roughly the number of stars which have companions, and to assess how many of these companions may themselves be stars, black dwarfs or true planets. Apparently the vast majority of stars have one or more secondaries, and, although the calculations are rather uncertain, possibly about 20 per cent of stars of classes F5 to M have planetary companions.

By careful photographic techniques it is possible to chart the proper motion of nearby stars. In the absence of any companions the proper motion track should appear as a straight line, but the presence of other bodies will cause a 'wobble'; from this it is possible to estimate the mass and distance of its companions. The work is naturally very difficult, but at least two stars (and as many as seven) have been suspected of having planet-sized companions. Recently however, considerable doubt has been expressed about these determinations, which have been largely the work of a single observatory. Even the cases of ε Eridani, which had been thought to have a massive planet about 6 times the mass of Jupiter, and Barnard's star (a faint red dwarf and one of the closest stars), suspected of having two planets of about 0·9 and 0·4 Jupiter masses, must now be considered suspect. It will probably be necessary to await more advanced methods which will allow planets to be detected directly (such as the proposed Project Orion system or, more probably, the Space Telescope) for this matter to be resolved – or at least for some progress to be made. It is likely to be a long time before Earth-sized planets become detectable by any means.