1 The Plasma Universe

1.1 Plasma, a Matter of State

A plasma has always been described as the fourth state of matter, the other three being the solid, the liquid, and the gas. A solid transforms into a liquid by heating (ice into water); heating transforms a liquid into a gas (water into water vapor). When a gas is heated to a rather high temperature, the outermost electrons are detached from the gas atoms and the remaining part of the atoms, called ions, acquire positive electric charge. A mixture of the positively charged ions and the negatively charged electrons is formed. This mixture of a sufficiently large number of ions and electrons is called a plasma, a term borrowed from the blood plasma in which the red blood corpuscles and other organisms float. The name plasma for this ionized gas was first suggested by Irving Langmuir in 1939 while he was studying the electric discharges of gases by passing a high electric current through a gas of Cesium atoms.

But this is not how Nature did it!

Nature began with the plasma. Cooling of the plasma converted it into a gas. Cooling of the gas converted it into a liquid. Cooling of the liquid converted it into a solid.

Even though a plasma is not a result of a phase transition in the manner of ice–water–vapor, it is considered to be a state of matter because the characteristics of a plasma are significantly different from its parent neutral gas. A plasma, similar to a gas, has no definite shape or volume. However, unlike a gas, a plasma has a high electrical conductivity; not all its constituent particles behave alike; the plasma particles can have Maxwellian velocity distributions with different temperatures; they can have even non-Maxwellian velocity distributions and interactions among the plasma particles are more often than not collective wherein a large number of particles get in phase and act cooperatively with other particles and waves in the system.

1.2 Plasma, the First State of Matter

Most astronomers believe that the universe began in a big bang about 15 billion years ago. There was an explosion of a not-so-well-understood state of matter under not-so-well-known extreme conditions of density and temperature. The aftermath of the explosion was the cooling and the expansion that continues till date.

It was first observed by Edwin Hubble in 1930, and gloriously reconfirmed by the Hubble Space (optical) Telescope at present, that the galaxies are rushing away from each other at high speeds. The present state of the universe when extrapolated back in time, using the known laws of physics, compels us to believe that the universe was extremely hot and dense in its infancy. In the beginning there was intense radiation, the photons, that produced equal amounts of matter and antimatter (particles with equal masses and equal and opposite electric charges such as electrons and positrons). And a plasma soup of particles and antiparticles was all there was.

Thus a plasma is the first state of matter out of which all the other states of matter originated.

The particles and the antiparticles, could, however, recombine back into radiation and this would go on until physics would forbid further production of particles and their recombination. To our good fortune, there is a tiny difference between the amounts of matter and antimatter and this tiny difference drove the evolution of the universe to what it is today. The cause of this difference is still not well understood. The quarks and the antiquarks constituted the very first, after ten microseconds of the big bang, plasma called the quark–gluon plasma (Fig. 1.1). The gluons are the glue that binds the quarks together. The quarks and the antiquarks are the building blocks of protons and neutrons. Scientists at CERN believe that they have been able to create such a state of quark–gluon plasma through the lead ion–lead ion collisions during which the ions break up into their constitutive quarks.

The electrons and the positrons were created from the decay of high-energy photons. During the period between the microsecond to the tenth of a second since the big bang, the protons, the neutrons, and other particles came into being from the quarks. At three minutes after the big bang explosion, the nuclear reactions set in. The neutrons began to decay into protons, electrons, and neutrinos (Fig. 1.2). The mass of a neutron is more than the mass of a proton. The difference in the rest masses (Δm) of the neutron and the proton is, by Einstein's mass energy relation, converted into energy Δmc^2 where c is the speed of light.

Two protons fused together to form deuterium (Fig.1.3). This reaction needs energy input to overcome the Coulomb repulsion between the positively charged protons. One proton is converted into a neutron and a positron is emitted along with a neutrino.

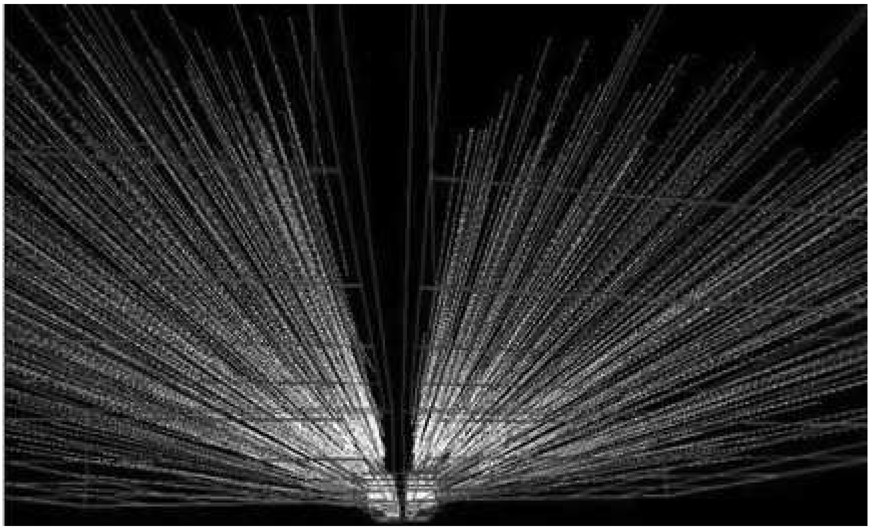

Figure 1.1 The little bang of a lead ion–lead ion collision as seen in NA49 CERN-EX-9600007. This is an image of an actual lead ion–lead ion collision taken from tracking detectors on the NA49 experiment. The collisions produce a very complicated array of hadrons as the heavy ions break up and create a new state of matter known as the quark–gluon plasma, credit: CERN.

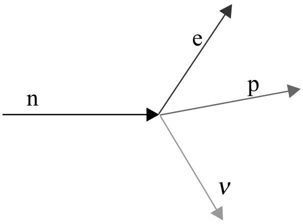

Figure 1.2 A neutron (n) has a life time of about 10 minutes after which it decays into a proton (p), an electron (e), and a neutrino (ν).

The deuterium nucleus, D(p,n), consists of one proton and one neutron.

One deuterium nucleus fuses with a proton to produce helium three nucleus He(2p,n), containing two protons and one neutron, gamma rays along with a release of 5.49 million electron volts (MeV) of (energy Fig. 1.4).

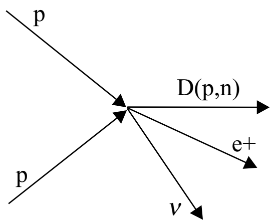

Figure 1.3 Two protons (p) fuse together to produce a deuterium nucleus D(p,n), a positron (e^+), and a neutrino (ν).

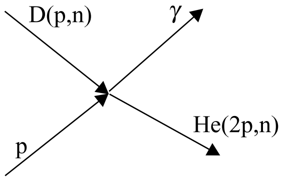

Figure 1.4 A deuterium nucleus D(p,n) fuses with a proton (p) to produce helium three, He(2p,n), and gamma rays γ.

Two helium three nuclei He(2p,n) fuse together to produce helium four nucleus, He(2p,2n), and two protons along with a release of 12.86 MeV of energy. This completes the cycle of proton–proton fusion (Fig. 1.5); remember we started with two protons.

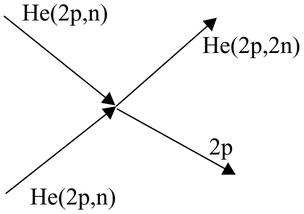

Figure 1.5 Two helium three nuclei He(2p,n) fuse to produce one helium four nucleus, He(2p,2n), and two protons (p).

One helium four nucleus fuses with one helium three nucleus to produce a nucleus of beryllium seven, Be(4p,3n), along with a release of 1.59 MeV of energy (Fig. 1.6). Lithium seven is an unstable nucleus. Only a small amount of lithium seven is formed in the primordial nucleosynthesis.

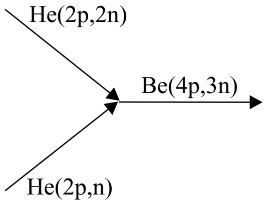

Figure 1.6 Production of beryllium, Be(4p,3n), nucleus.

This is as far as the thermonuclear fusion, at this stage, contributes to the formation of elements. The rest of the elements of the periodic table would be manufactured in stars and their supernovae explosions. These fusion processes continued up to the fifteenth minute since the big bang. At this epoch, the temperature of the universe is about a million degrees. The universe is a fully ionized plasma consisting of photons, nuclei, and electrons.

The primordial helium abundance of 25 percent by mass is a robust prediction of the big bang model and it has been sufficiently confirmed by observing the very distant objects such as quasars or objects in which stellar nucleosynthesis has not occurred. The agreement between observations and the theoretical prediction for the lithium abundance is not so good. Recently, scientists at the Brookhaven National Laboratory of the department of the US atomic energy have created the hottest temperatures ever, a whopping four trillion degrees at which the protons and the neutrons melt to produce a quark–gluon plasma, akin to the earliest, the primeval plasma from which the universe is believed to have emerged.

1.3 Plasma in Superclusters of Galaxies

The largest gravitationally bound structures in the universe are the superclusters of galaxies, each containing thousands of clusters of galaxies (Fig. 1.7).

Superclusters of galaxies have typical dimensions of 100 megaparsecs (one parsec = 3×10^{18}cm) and carry signatures of the initial conditions in the early universe. The clusters of galaxies in a supercluster swim through the intercluster plasma with temperature of several million degrees Kelvin, an electron density $\approx 10^{-3}$ cm^{-3} and perhaps a magnetic field of the order of a microgauss. The observed emission in X-rays (Fig. 1.8) confirms the existence of the hot intercluster plasma.

The electrons of this hot plasma are so energetic that they impart some of their energy to the photons of the cosmic microwave radiation producing an observable bump in its otherwise smooth nearly perfect black body spectrum.

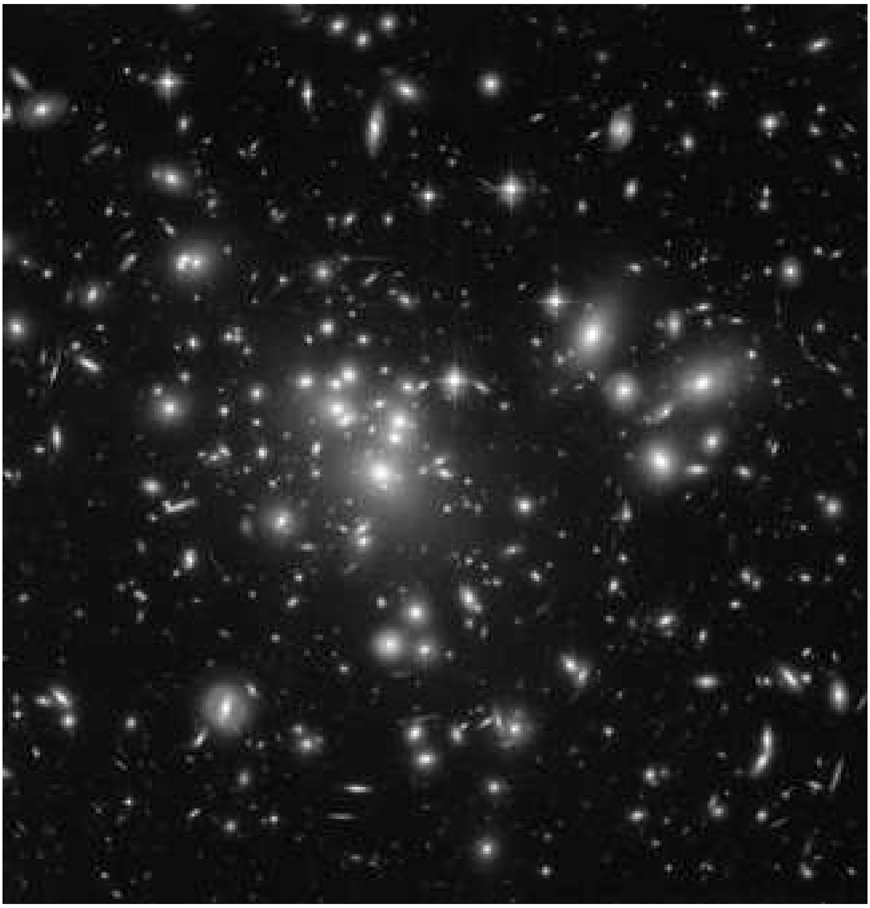

Figure 1.7 Abell supercluster 1689 containing several clusters of galaxies, credit: NASA/ESA.

1.4 Intergalactic Plasma

The million degree intergalactic plasma was opaque to the radiation and both radiation and the ionized matter were strongly coupled and evolved together. The plasma was too hot to form atoms. As the universe expanded, it cooled. It took about a million years for the universe to cool down to a temperature of 3000 K, appropriate for the recombination of electrons and nuclei to form the first neutral matter. This is known as the recombination epoch characterized by a partially ionized plasma. The matter and radiation decoupled. The thermal radiation emitted by the matter at 3000 K pervaded the universe unchallenged by the mostly neutral matter. This is the cosmic microwave background radiation.

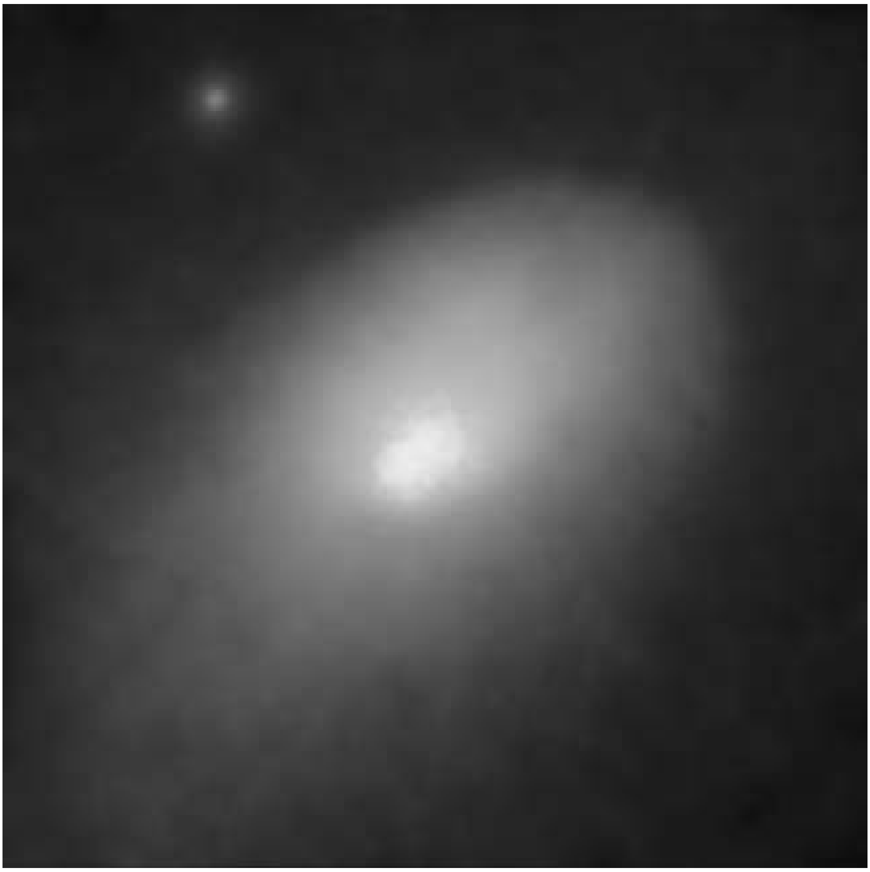

Figure 1.8 X-ray image of galaxy cluster Abell 2412. The image on the right was taken on August 20, 1999 with the Chandra X-ray Observatory's 0.3–10.0 keV Advanced CCD Imaging Spectrometer (ACIS), and covers an area of 7.5 × 7.2 arc minutes. It shows a colossal cosmic "weather system" produced by the collision of two giant clusters of galaxies. For the first time, the pressure fronts in the system have been traced in detail, and show a bright, but relatively cool, 50 million degree Celsius central region (white) embedded in a large elongated cloud of 70 million degree Celsius gas all of which is rolling in a faint "atmosphere" of 100 million degree Celsius gas. The bright source in the upper left is an active galaxy in the cluster, credit: http://www.en.wikipedia.org/wiki/File: *Abell2142 chandra xray.jpg*. This file is in the public domain because it was solely created by NASA.

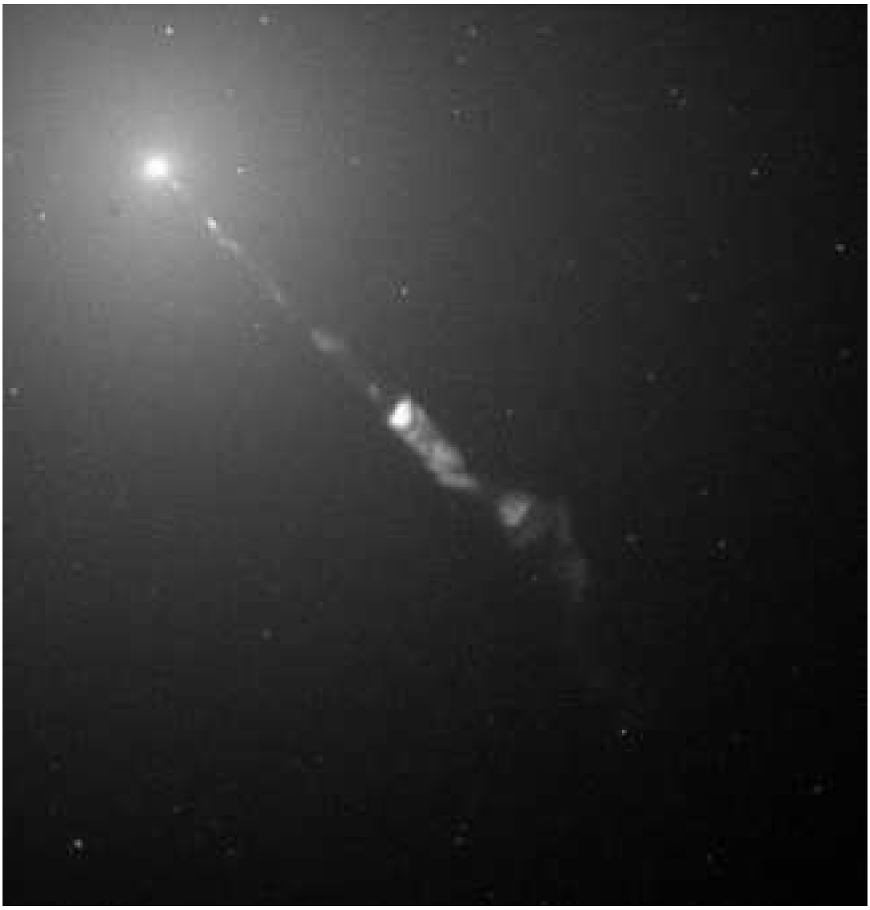

Figure 1.9 A Jet from Galaxy M87 Image, credit: J.A. Biretta et al., Hubble Heritage Team (STScI /AURA, NASA).

The expansion and the cooling has brought the present temperature of the universe to 2.7 K as inferred from the observed spectrum of the cosmic microwave background radiation. Although the neutral matter is mostly homogeneously distributed, as the near isotropy of the cosmic microwave background radiation tells us, there does exist a very very small anisotropy in the radiation, which betrays a very small clumping of the matter. These clumps would then grow into stars and galaxies by attracting more matter toward them due to the attractive gravitational forces. The matter in between the galaxies is again hot, ionized and magnetized and this is the intergalactic plasma. The intergalactic plasma clouds are of enormous dimensions, harboring several galaxies and black holes. The plasma is observed through the detection of the synchrotron radiation, which is emitted by electrons gyrating in a magnetic field. The radiation is in the radio part of the electromagnetic spectrum and there are several big radio telescopes such as the world's largest radio telescope at Arecibo, Puerto Rico, capable of detecting this radiation. The properties of the radiation tell us that the intergalactic plasma has a particle density of $\approx 10^{-5} - 10^{-4}$ per cubic centimeter, a temperature of $\approx 10^{6} - 10^{7}$ K and a magnetic field of $\approx 10^{-9}$ Gauss. Compare it with Earth's magnetic field of about 0.3 Gauss. The picture (Fig. 1.9) shows the brightest central region where a plasma jet from the galaxy M 87 hits the intergalactic medium.

1.5 Galactic Plasma

A galaxy is made up of stars, nebulae (star-forming regions), gas, dust, magnetic field, and the medium in between the stars, the interstellar medium. Thus the temperature of a region and hence its state of ionization depends on its location in a galaxy. Around the galactic center exists a hot magnetized plasma observed through its emission in the radio part of the electromagnetic radiation. One sees plasma loops where the plasma illuminates the bipolar magnetic field configuration.

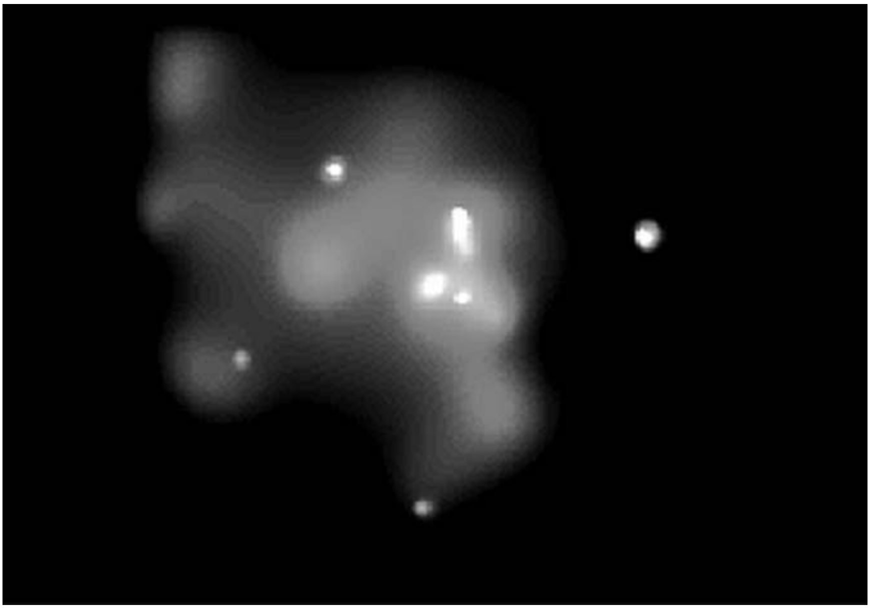

Figure 1.10 Chandra X-ray image of the innermost 10 light years at the center of our galaxy, credit: NASA/MIT/PSU.

The observed radio radiation has the characteristics of the synchrotron radiation and this reveals that the typical plasma density is 0.04 per cubic centimeter, the magnetic field is of the order of a milliGauss, and the temperature is of the order of hundred million degree Kelvin. A huge envelope of plasma, a kind of galactic corona (a crown) has been observed in our own galaxy, the Milky Way, using the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. The plasma envelope may extend as far as the nearest galaxies, the magellanic clouds. Figure (1.10) shows the central region of our galaxy, which harbors the supermassive black-hole candidate Sagittarius A* (larger white dot at the very center of the image). The X-ray emission is from the plasma surrounding the black hole. The millions of degree plasma is produced by the shock waves caused by supernova explosions in the galaxy.

1.6 Interstellar Plasma

There are huge spaces among the stars in a galaxy. The spaces are so huge that the stars almost never collide. Nevertheless, the interstellar medium is sizzling and buzzing because stars are in the habit of spewing out hot winds. Just as our sun blows the hot solar wind. Stars also, not so infrequently, explode, the supernovae explosions, throwing large amounts of steaming streaming plasma in their vicinity. The interstellar medium is a potpurri of hot and cold regions containing plasma, gas, and dust (Fig. 1.11).

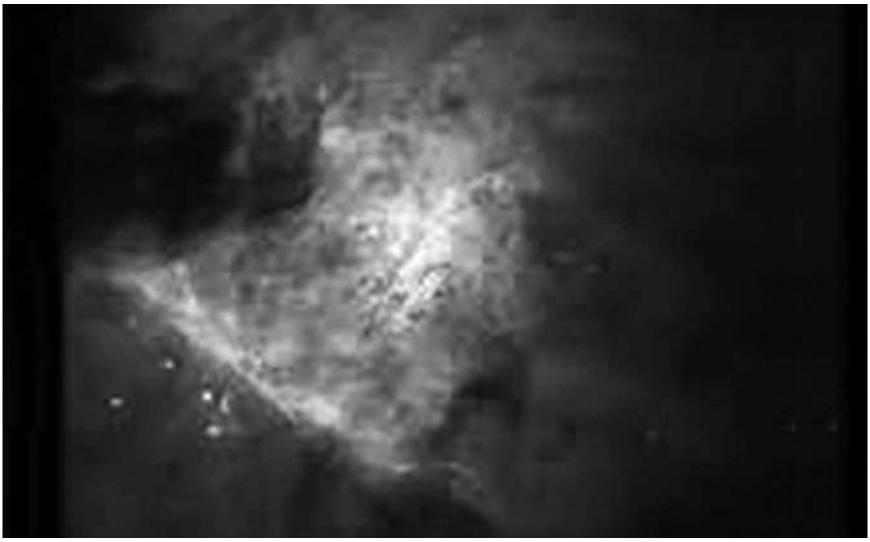

Figure 1.11 Stars, gas, and dust in the orion nebula, credit: hubblesite, NASA.