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Introducing the stars and nebulae

To people of ancient times the universe was a stable, if not always secure, place, created, so it seemed, for the sole convenience of humanity. That man's abode, the earth, should occupy the dominant central position could scarcely be doubted, while the sun's justification for existence was to provide mankind with light and life-sustaining energy. The gleaming stars, fixed in the revolving celestial sphere, were regarded as bits of a cosmic mural designed to beautify the night.

It was only natural, too, that the details of the celestial scenery should have become identified with heroes and objects of mythology, identifications that remain in current use as names of star groups, or constellations. Thus the unexcelled constellation of the winter sky is Orion, the mighty hunter whose club is upraised against the charging bull Taurus (Fig. 1.1). Three bright equally spaced stars represent his belt; a misty group of stars forms his sword. Behind Orion his two dogs pursue Lepus, the fleeing hare. Marking the eye of the greater dog is sparkling Sirius, the Dog Star. To the ancient Egyptians Sirius was the popular Nile star, whose rising just before the sun foretold the impending flooding of the Nile. Sirius was distasteful to the Greeks, however, for they believed that the blending of its rays with those of the August sun produced hot summer weather. In Persian mythology, Sirius was Tishtrya, the Great Rain Star, who battled Apaosha, the demon of drought. Immortalized in the constellations are Hercules, the Nemean Lion, Hydra, Perseus and Andromeda, and the equipment of gods and heroes – Jason's ship *Argo*, the Harp of Orpheus, and the arrow from the bow of Chiron.

With the passage of time, these legends, which represented people's earliest attempts to relate themselves to their surroundings, became replaced by objective studies of the stars. The astronomical explorer has found the universe a treasure-house of existing discoveries wherein, to add zest to the chase, each great addition to knowledge has brought forth scores of fresh unsolved problems. Mysteries will continue to appear as long as there are people to ponder them.

In this book we embark on a journey of astronomical exploration in which the reader may sample a little of the thrill of discovery. During the course of our journey we shall probe the seething atmospheres of the stars and even dig into the interiors themselves. We shall encounter all kinds of curious objects, not only single stars, multiple stars, dwarf stars, giant stars, pulsating stars, stars with fantastic magnetic

Fig. 1.1. Mythological map of the sky in the neighborhood of Orion.

fields, and some whose surface layers are occasionally torn off in cataclysmic stellar explosions, but also clouds of gas and smog, the bizarre pulsars, sources of X-rays and gamma rays, and mysterious emitters of huge amounts of energy, whose nature is not understood at the present time.

Our course among the stars has already been charted, for, in broad outlines at least, the geography of the local regions of the universe is known. The earth is but one of a family of planets, satellites, planetoids, and meteoric particles that revolve periodically about the sun. In its turn the sun is but one of a vast host of stars, about two hundred thousand million, which are grouped together in the form of a thin lens-like system. This stellar system, which contains all naked-eye stars as well as many millions too faint to appear visually, is known as the Galaxy or the Milky Way System. The sun's position is at a point approximately two-thirds of the way from the center to the circumference. The broad outlines of galactic structure are now pretty well established, thanks largely to new observational techniques described in

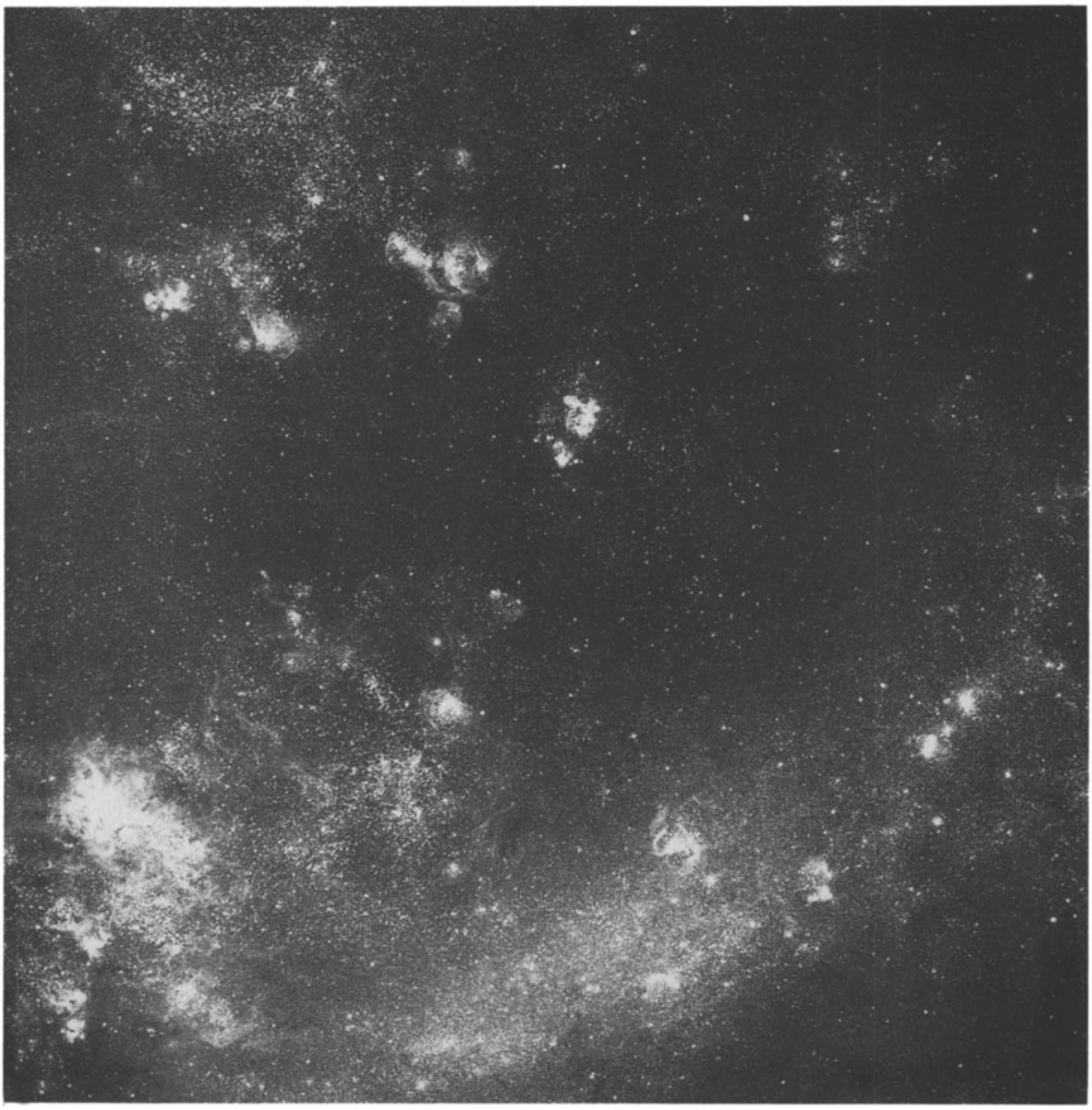

Fig. 1.2. The main part of the Large Magellanic Cloud. This galaxy has a large number of nebulosities or glowing clouds of gas as well as many stars and star clusters. The most spectacular nebula is 30 Doradus, at the centre of the nebulosities lower left (see frontispiece). (Photographed with the Uppsala Schmidt Camera at Mount Stromlo Observatory, courtesy Bengt Westerlund.)

later chapters, but many details still elude us, since we are within the system. Our Galaxy, however, is but one of thousands of millions of far-flung systems that lie in the observable universe. The nearest external galaxy is the Large Magellanic Cloud in the southern hemisphere (See Fig. 1.2). Another example is the Triangulum Spiral, M33 (i.e. no. 33 in the catalogue of nebulae and clusters compiled by Charles Messier). In structure our Galaxy more closely resembles (Fig. 1.3) than the

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Fig. 1.3. The Triangulum Spiral, Messier 33. This spiral galaxy, which is much smaller than the Andromeda Spiral, M31, or our own Galaxy, is seen nearly in plan. It has well-defined spiral arms but no prominent central bulge. There are large numbers of gaseous nebulae and luminous stars, similar to those found in our own Galaxy or in the Magellanic Clouds. (Lick Observatory, University of California.)

irregular Magellanic Clouds, but it is much larger than M33. Studies of the Andromeda Spiral, M31, have revealed its similarity in size, form, and stellar content to our Milky Way. In both of these galaxies there are pronounced bulges and many of the stars in the main disks are arranged in well-defined spiral arms. Our emphasis is going to be on the gaseous nebular, dusty, and stellar contents of our own Galaxy, but we shall also make reference to other systems.

Despite the space-penetrating powers of large optical telescopes as well as powerful radio telescopes there is no indication that we have reached the boundaries of the universe, if any indeed exist. Most of our tour of exploration will be within the confines of our own Galaxy or the local group of galaxies, but we have reason to believe that our sample is more or less typical of the universe as a whole.

The local group of galaxies – Andromeda (M31) and its companions M32 and NGC 205, the Triangulum Spiral (M33), the two Magellanic Clouds, and several fainter objects such as NGC 6822 and IC 10, and of course our own Galaxy – contains samples of most of the principal types of stellar systems. Their relative proximity and the advent of new, large telescopes equipped with efficient instrumentation make them attractive objects for studies of gaseous nebulae, clusters, and individual stars.

The voyages between stars are likely to be smoggy, for interstellar space is strewn with great clouds of gas and solid grains of dust that dim and redden the light from the stars beyond. Like powerful searchlights, bright stars illuminate many of these clouds, revealing them to the astronomical explorer as bright nebulae. This interstellar matter is spread so thinly that, by comparison, the density of gas present in the best laboratory vacuum seems enormous. Yet, despite its extreme tenuity, enough dust is scattered between the stars to hide from view distant regions of our Galaxy. The interstellar gas emits radiation in the optical, infrared (heat), ultraviolet, and radio-frequency ranges, and much progress has been made by studying the interstellar matter particularly with radio telescopes and infrared detectors.

In addition to the above-mentioned radiations (all of which are examples of what are called electromagnetic radiation (see Chapter 2), fast-moving, stripped nuclei of atoms of familiar elements, mostly hydrogen, are found in space and impinge upon the earth. These are called cosmic rays. They are actually particles, and their properties are discussed in Chapter 12.

One of the features of our tour of discovery is that it can be made without the usual perils of exploration. In fact, owing to the magical powers of light rays, X-rays, gamma rays, and radio waves, we can explore far corners of the universe without leaving the comfort and security of the earth. Radiations that are absorbed in the earth's atmosphere (most of the infrared or heat radiation, some radio waves, and all X-rays and gamma rays) can be studied by rockets and satellites flown above the earth's atmosphere.

The astronomer of a century ago mapped the positions of stars upon the sky and designated their locations much as a geographer maps the earth from accurate measurements of latitude and longitude upon its surface. The positions of the stars are found from the directions of the light rays they emit, but direction is only one characteristic of light rays. Starlight also carries a message about the physical nature of the stars, their masses, brightnesses, chemical compositions, surface temperatures, and even the nature of their internal structure. Radio waves from clouds of interstellar gas tell something about their temperature, density, and chemical composition, and reveal the presence of large-scale magnetic fields. Only relatively recently have we learned to read these hieroglyphic messages from the stars and nebulae. Modern physics, which describes how atoms behave and how they can radiate light, has made this analysis possible. The story of the interpretation of stars and nebulae, so highly dependent on the findings of modern physics, is one emphasized in this book.

We shall start by describing the most obvious properties of stars and nebulae as revealed by their optical radiation. Historically, of course, no other option was possible. Restriction to the optical region led to the conception of an essentially 'thermal' universe. Radiation was emitted by hot bodies and subsequently scattered and absorbed by cooler objects. The development of radio astronomy, ultraviolet, and X-ray techniques, showed this view to be much too simplistic and opened the door to the exciting vision of a more complex universe.

Stellar distances and brightnesses

Four obvious questions will occur immediately to anyone interested in probing the physical nature of the stars, namely, how distant, how bright, how big, and how heavy they are. To answer these questions we must employ measuring rods and scales that can be applied over large distances. An astronomer uses the same principle to measure the distance of a star that a surveyor uses to measure the distance across a lake. Fig. 1.4a illustrates the surveyor's problem; Fig. 1.4b the astronomer's. The former measures the length of the line AB and the angles ABC and CAB. The determination of two angles and an included side serves to fix the dimensions of the triangle ABC and side AC or BC may be computed. Analogously, the astronomer uses as his baseline AB the diameter of the earth's orbit around the sun. When the earth is at A the star lies in the direction AC; six months later the earth is at B and direction of the star is now BC. One-half of the angle of displacement, i.e. the angle BCD or ACD, is called the parallax of the star. The amount of the shift clearly depends on the proximity of the star, the more distant ones being the least affected. (Actually, the star is not at rest but is moving in a straight line with respect to the sun, and additional observations must be secured to obtain both the parallax and the motion of the star across the line of sight. The motion across the line of sight is called the 'proper motion' and is measured in angular units.)

The unit of stellar parallax is the second of arc (or arcsec or ″); it is 1/3600 of a degree, i.e. it is about the angle subtended by a small coin at a distance of 4 kilometers (2.5 miles). So small an angle cannot be distinguished with the unaided eye, but modern telescopes permit parallaxes of 0.01 arcsecs to be measured with fair accuracy. An astrometric satellite to replace the ill-fated Hipparchos, would enable the measurement of the parallaxes of about 100 000 stars to an accuracy of 0.002

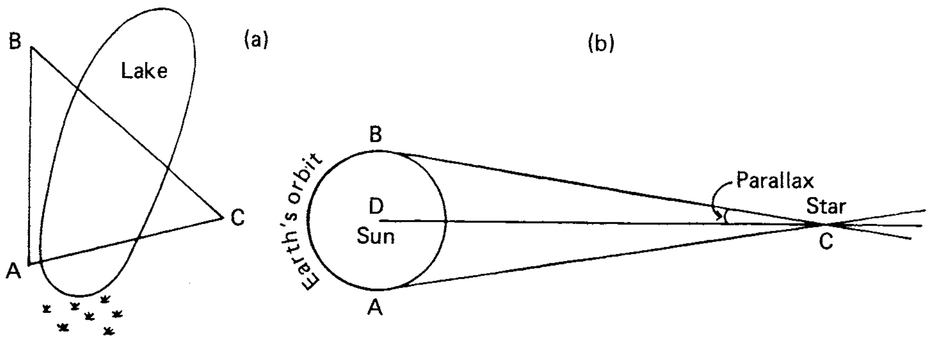

Fig. 1.4. Measurement of distances by triangulation. (a) The surveyor measures the distance A to B, plus the angles at A and B, from which the triangle ABC can be constructed and the distances across the lake obtained. (b) The astronomer uses the diameter of the earth's orbit as the baseline and measures the parallax angle of the star.

arcsecs, that is about five times better than the best ground-based instrument. This accuracy of angular measurement corresponds roughly to the angle subtended by a man standing on the moon. In the radio range, even smaller angles can be measured with the Very Long Baseline Intercontinental (VLBI) radio array.

The parallax of α Centauri, the nearest star, is 0.752 arcsecs, corresponding to a distance of about forty million million kilometers or twenty-five million million miles. To express distances such as this in kilometers or miles is more awkward than giving the distance from London to New York in millimeters; hence stellar distances are often expressed in light-years, at least in popular writing. One light-year, the distance traversed in one year by a ray of light traveling at 299 793 kilometers (186 000 miles) per second, is nearly 9.5 million million kilometers (6 million million miles). The nearest star is 4.33 light-years away; Sirius, which appears as the brightest star in the sky, is at a distance of 8.7 light-years, and our entire system of stars, the Milky Way, probably measures 100 000 light-years across. On such a scale our solar system seems tiny indeed: if we represent the distance from the earth to the sun by 15 millimeters, 1 light-year corresponds very nearly to 1 kilometer. (If the distance to the sun is represented by one inch a light-year is about 1 mile.)

Two other units of distance, the astronomical unit and the parsec, are also useful in astronomy. For expressing distances intermediate between the kilometer (or mile) and the light-year, the radius of the earth's orbit, which is called the astronomical unit (abbreviated AU), is commonly used. (This unit should not be confused with the ångstrom unit, abbreviated Å, used to express the wavelength of light.) The parsec is the distance of a star whose parallax is 1 arcsec; it is equal to 206 265 AU or 3.26 light-years. Since parallax is inversely proportional to distance, the distance in parsecs is simply the reciprocal of the parallax in arcsecs. Thus a star 10 parsecs or 32.6 light-years away has a parallax of 0.1 arcsec, a star 100 parsecs or 326 light-years away has a parallax of 0.01 arcsec and so on.

The surveyor's method of measuring parallax is inadequate for any but the very nearest stars; angles smaller than 0.01 arcsec cannot be measured accurately by ground-based techniques and even our best-designed astrometric satellites will be able to supply parallaxes for stars only within about 500 parsecs, that is only to about 1/15th the distance to the center of the Galaxy. Fortunately, astronomers have devised ways of estimating the distances of remoter stars. One can take advantage of the fact that the stars are in motion, both in regard to one another and with respect to the sun. The actual velocity of motion along the line of sight can be measured by the Doppler effect (see Chapter 2). Then, by measuring the apparent angular motions of selected stars across the sky in different parts of the celestial sphere, one can obtain average or statistical distances much as one could estimate the distance of a lighted speedboat seen on a harbor at night if one knew its actual speed in the water. Other methods, which are described later, are based on the principle that we measure accurately the intrinsic luminosities of certain kinds of stars that we can recognize in distant parts of the Galaxy or even in other stellar systems. Then, from the apparent brightness of the star and its known intrinsic brightness, we can get its distance, since the brightness of a point source of light diminishes as the square of its distance. If α Centauri were 8.66 instead of 4.33 light-years away it would appear one-fourth as bright.

Conversely, if the distance of a star has been found, we may, knowing its apparent brightness, establish its true brightness. Our current practice of expressing the apparent brightness of a star as seen in the sky in terms of magnitudes was initiated 2000 years ago, when ancient astronomers graded the stars from the first (brightest) to the sixth magnitude, the latter being just barely visible to the naked eye. For more than a century, the magnitude scale has been so adjusted that a star of the first magnitude is exactly 100 times as bright as one of the sixth magnitude. The scale goes as a geometrical progression, that is, the brightness ratio corresponding to a one-magnitude step is constant. Thus, a first-magnitude star is 2.512 times as bright as a second-magnitude star, which in turn is 2.512 times as bright as a third-magnitude star, and so on. The original scale of six magnitudes has been extended to include the very faint as well as the very bright stars. Stars as faint as the 23rd or 24th magnitude can be detected with the aid of photoelectric cells or with what are called charge-coupled devices (CCDs) with large telescopes. The brighter stars in the sky, like Aldebaran and Altair, are of the first magnitude. The two very brightest stars in the sky, however, have negative magnitudes; thus the magnitude of Canopus is -0.7, and that of Sirius is -1.6. On the same scale the apparent magnitude of the full moon is -12.7 and that of the sun is -26.8.

Stellar magnitudes may be measured with the eye or with other light-sensitive devices such as the photographic plate, with the photoelectric cell, or with charge-coupled devices, with the aid of appropriate filters (see Chapter 6). By using different filters the color of a star may be measured. The visual magnitudes measured by early observers have been replaced by photoelectric magnitudes measured with a yellow filter – the so called V-magnitudes. If we wish to express the apparent brightness of a star taking into account all the radiation it emits – infrared, red, green, blue, violet, and ultraviolet (Chapter 2) – we use the bolometric magnitude. The bolometric magnitude is a quantity derived from the observations and the temperature of the star (see Chapter 4); it will be an observed quantity only when stellar brightnesses can be measured from above the earth's atmosphere. Both very cool and very hot stars are very much brighter bolometrically than visually, since most of their energy is emitted as radiation to which our eyes are not sensitive.

Were all stars equally distant from us, their apparent magnitudes would represent their true relative brightnesses. In practice, we define the intrinsic luminosity of a star by its so-called absolute magnitude, which is the apparent magnitude it would have at a standard distance of 10 parsecs = 32.6 light-years (see Appendix E). The bolometric absolute magnitude of the sun is +4.69. This is the quantity that is important when we want to actually compare the energy outputs of stars. The absolute 'photoelectric visual' magnitude of the sun is +4.83 (according to Popper; see Appendix D), which means that at a distance of 10 parsecs it would be comfortably visible on a clear moonless night. Arcturus, whose distance is about 33 light-years, would appear at about its present brightness. Sirius would be about 1/14th as bright as at present and no longer conspicuous. Rigel, in the constellation Orion, which is 50 000 times brighter than the sun, would outshine any object in the present night sky save the moon.

Until recently, all of what we knew of the universe had been discovered by the detection and measurement of radiation by optical methods, that is with devices employing ordinary lenses and mirrors. A great technological breakthrough was provided by radio astronomy. It was found that stars, gas clouds, and galaxies also emit radio waves in addition to light and heat waves. Many radio telescopes are parabolic reflectors, thus resembling instruments of the optical astronomer, but even the largest of these give limited angular resolution. Modern developments entail the use of arrays of radio reflectors (or 'dishes' as they are commonly called). The individual dishes can be moved relative to one another along tracks and placed in different positions and configurations. With such a device, which is called an interferometer, it is possible to obtain observations of very high angular resolution. The largest and most successful example of this type of telescope is the Very Large Array (VLA) in New Mexico in the USA. It is also possible to link radio telescopes in different hemispheres. Then, measurements of a thousandth of an arcsec are possible.

As seen through the eye of a radio telescope, the sky has a totally different 'appearance' from that in visible light. Most of the radio radiation comes from gas clouds rather than from individual stars; hence the familiar constellations are not seen in the radio telescope, but are replaced by a variety of radio sources that have quite a different arrangement in the sky.

Weighing the stars

The motion of the earth about the sun makes possible the determination of stellar distances. Curiously enough, the circling of one star about another permits the determination of stellar masses. Like all planets, and stars too for that matter, the earth is imbued with a wanderlust. Were the restraining influence of the sun's gravitational attraction suddenly to be removed, the earth would fly off in a straight line and eventually lose itself in interstellar space. Just as the earth is kept in its path by the gravitational attraction of the sun, so also are a large number of stars denied a carefree existence by the gravitational attractions of companion stars. Stars so inhibited pursue circular or ellipitical orbits about each other. The more massive the two stars, the faster will they move about each other, which we may see from a simple analogy.

Suppose we were in a spaceship in interstellar space, where there was no gravitational attraction, so that we floated freely about, and suppose further that it was necessary to measure the mass of a small solid object. Since gravity would not exist inside the spaceship, we could not just put the object on a scale and weigh it; some other technique would have to be used. If a spring scale were available, the unknown mass could be found by attaching the object to the scale and swinging them both in a circle at the end of a string. The spring scale would measure the tension in the string, which would depend on the speed of revolution and the mass of the object. The tension would be greater, the greater the mass or the greater the speed of revolution. From the measured tension and the speed of whirling, we could find the mass of the object.

By an analogous procedure the astromomer weighs the stars. The rate of motion of two stars in a double-star system about each other depends on the gravitational force between them. This attractive force, analogous to the tension in the string, is proportional to the masses of the stars (and also to the inverse square of the distance between them), according to Newton's law of gravitation. By observing the time required for the two stars to circle each other (the period) and measuring the distance between them, we find the restraining force and hence the masses.

Double-star, or binary, systems are common among the stars. In fact, groups have been found in which three, four, five, and even six stars revolve about one another. Some of these multiple systems merit a brief description.

α Centauri consists of two stars that revolve about each other in 80 years in rather elongated ellipitical orbits, so that at times they approach as near as 11 astronomical units (a little more than the distance of Saturn from the sun) and sometimes they recede to 35 astronomical units (nearly the distance of Pluto from the sun). The brighter component is almost a duplicate of the sun, save that it is a little brighter and perhaps a little heavier and a little hotter. The fainter component is cooler and less massive. In 1915, R.T.A. Innes discovered a faint red star 2 degrees away that shares the same motion through space as α Centauri but is 15 000 times fainter than the sun. It is at least 10 000 or 12 000 astronomical units from the brighter pair and must take about a million years to complete its orbit.

Of particular interest is the lesser Dog Star, Procyon, a binary with a period of 40.65 years and a mean separation of 4.55 arcsecs, which corresponds to a distance of 15.8 astronomical units, somewhat less than the separation of the sun and Uranus. The brighter (V-magnitude of 0.35) star has a mass about 1.75 times that of the sun. The companion is a very faint star (with a magnitude of 10.8). It is an aged, superdense star, commonly called a white dwarf (see Chapter 9). Now the orbit of