1

General Introduction

1.1 Introduction

Many important topics in astrophysics involve the physics of ionized gases and the interpretation of their emission-line spectra. The subject is fascinating in itself. In addition, H II regions allow us to probe the evolution of the elements and the star-formation history of the far reaches of our own Galaxy, and of distant galaxies. Planetary nebulae let us see the outer remaining envelopes of dying stars. Supernova remnants allow us to observe material from the burned-out deep interiors of exploded, massive stars. Starburst galaxies, quasars, and QSOs are the most luminous objects in the universe, and hence the most distant that we can observe. Spectra can reveal details surrounding the first generations of star birth and the formation of the heavy elements in the young universe. All of these are subjects we shall cover in this book. Further applications, such as the properties of intergalactic material, X-ray flows, and primordial galaxies, though not treated here, are straightforward extensions of the physics that forms the spine of this volume.

1.2 Gaseous Nebulae

Gaseous nebulae are observed as bright extended objects in the sky. Those with the highest surface brightness, such as the Orion Nebula (NGC 1976) or the Ring Nebula (NGC 6720), are easily observed on direct images, or even at the eyepiece of a telescope. Many other nebulae that are intrinsically less luminous or that are more strongly affected by interstellar extinction are faint on ordinary images, but can be imaged on long exposures with filters that isolate a narrow wavelength region around a prominent nebular emission line, so that the background and foreground stellar and sky radiations are suppressed. The largest gaseous nebula in the sky is the Gum Nebula, which has an angular diameter of the order of 30°, while many familiar nebulae have sizes of the order of one degree, ranging down to the smallest objects at the limit of resolution of the largest telescopes. The surface brightness of a nebula is independent of its distance, but more distant nebulae have (on the average) smaller angular size and greater interstellar extinction; so the nearest members of any particular type of nebula tend to be the most-studied objects.

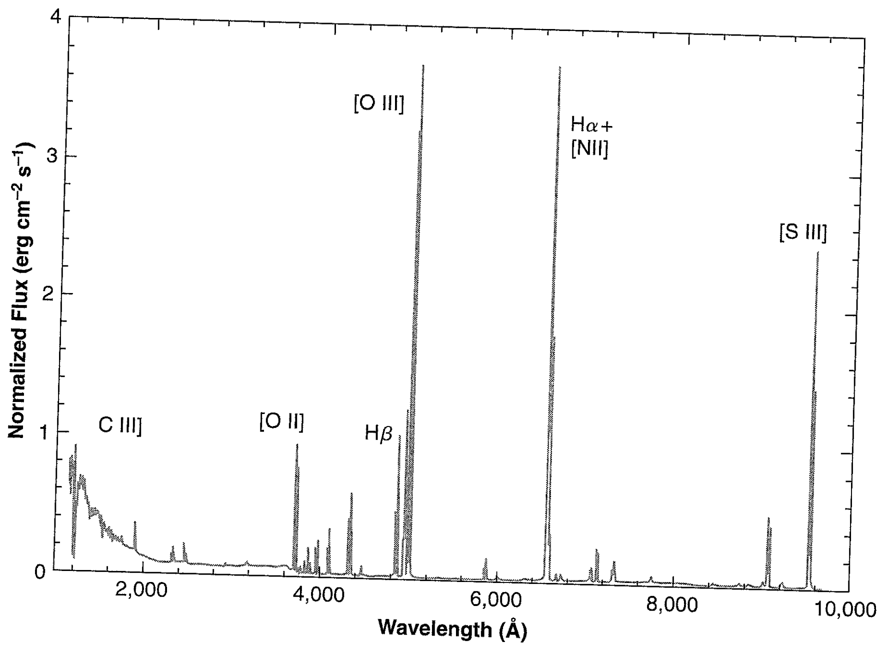

Figure 1.1

The ultraviolet, optical, and near infrared spectrum of inner regions of the Orion Nebula. A few of the strongest lines are identified in the plot; their wavelengths and those of all the other emission lines, from C III] $\lambda 1909$ to [S III] $\lambda\lambda 9069$, 9531 (except the H I and He I lines) may be found in Chapter 3. The flux scale is normalized to the flux in $H\beta = 1$. (Original data provided by Reginald Dufour and Jack Baldwin.)

Gaseous nebulae have emission-line spectra. Their spectra are dominated by forbidden lines of ions of common elements, such as [O III] $\lambda\lambda 4959$, 5007, the famous green nebular lines once thought to indicate the presence of the hypothetical element nebulium; [N II] $\lambda\lambda 6548$, 6583 and [S III] $\lambda\lambda 9069$, 9523 in the red; and [O II] $\lambda\lambda 3726$, 3729, the ultraviolet doublet which appears as a blended $\lambda 3727$ line on low-dispersion spectrograms of almost every nebula (Figure 1.1). In addition, the permitted lines of hydrogen, Hα $\lambda 6563$ in the red, Hβ $\lambda 4861$ in the blue, Hγ $\lambda 4340$ in the violet, and so on, are characteristic features of every nebular spectrum, as is He I $\lambda 5876$, which is considerably weaker, while He II $\lambda 4686$ occurs only in higher-ionization nebulae. Long-exposure spectrophotometric observations extending to faint intensities, show progressively weaker forbidden lines, as well as faint permitted lines of common elements, such as C II, C III, C IV, O II, and so on. Nebular emission-line spectra, of course, extend into the infrared, where [Ne II] $\lambda 12.8\ \mu$m and [O III] $\lambda 88.4\ \mu$m are among the strongest lines measured, and into the ultraviolet, where Mg II $\lambda\lambda 2796$, 2803, C III] $\lambda\lambda 1907$, 1909, C IV $\lambda\lambda 1548$, 1551, and even Lα $\lambda 1216$ are also observed. It is seldom possible to observe all important stages of ionization in a particular spectral region. In these cases one must model the physical system or obtain spectra

outside of the traditional visible/near-IR bands to get an accurate picture of the system in question.

Gaseous nebulae have weak continuous spectra, consisting of atomic and reflection components. The atomic continuum is emitted chiefly by free–bound transitions, mainly in the Paschen continuum of H I at $\lambda > 3646$ Å, and the Balmer continuum at 912 Å $< \lambda <$ 3646 Å. In addition, many nebulae have reflection continua consisting of starlight scattered by dust. The amount of dust varies from nebula to nebula, and the strength of this continuum fluctuates correspondingly. In the infrared, the nebular continuum is largely thermal radiation emitted by the dust.

In the radio-frequency region, emission nebulae have a reasonably strong continuous spectrum, mostly due to free–free emission or bremsstrahlung of thermal electrons accelerated on Coulomb collisions with protons. Superimposed on this continuum are weak emission lines of H, such as 109α at $\lambda = 6$ cm, resulting from bound–bound transitions between very high levels of H. Weaker radio recombination lines of He and still weaker lines of other elements can also be observed in the radio region, slightly shifted from the H lines by the isotope effect. In the infrared spectral region most nebulae have strong continuous spectra, emitted by heated dust particles within them. These emission continua have bands, some identified as resulting from silicate or graphite in the particles, others still not positively identified.

1.3 Observational Material

Nebulae emit a broad range of "light", by which we mean the full range of electromagnetic radiation, although only a few wavelengths pass easily through the Earth's atmosphere. Figure 1.2 shows the altitude above which atmospheric attenuation ("absorption") is negligible. Visible light, and some infrared and radio radiation, can be studied from the ground, but most other wavelength regions can only be observed from high-altitude aircraft, balloons, or orbit.

The resolution that can be achieved is limited by the telescope and the detector, and also by the refractive effects of the air. Spatial resolution is measured by the apparent diameter of a point source, usually expressed in arcsec. It is influenced by the aperture of the telescope, the number of resolution elements per unit area on the detector, and "seeing", the blurring of an image caused by refraction of light in the Earth's atmosphere. Spectroscopic resolution specifies the smallest wavelength or energy interval that can be discerned, and is usually measured in the most convenient units for a particular form of light. The angstrom unit is commonly used for the wavelength resolution $\delta\lambda$ in visible light. Resolution has the disadvantage that while 1Å resolution is very low resolution for $\lambda \approx 5$ Å X-rays, it is very high resolution for infrared wavelengths near 10,000 Å. The resolving power, the ratio $\lambda/\delta\lambda$, is more convenient for many purposes. It is inversely proportional to the radial-velocity resolution δu since $\lambda/\delta\lambda = c/\delta u$ for the Doppler effect. Resolving powers of 10^3–10^4 correspond to radial-velocity resolutions of 30–300 km s^{-1}. Typically, a radial velocity can be measured with an accuracy that is roughly a tenth of the velocity resolution, for lines that have symmetric profiles.

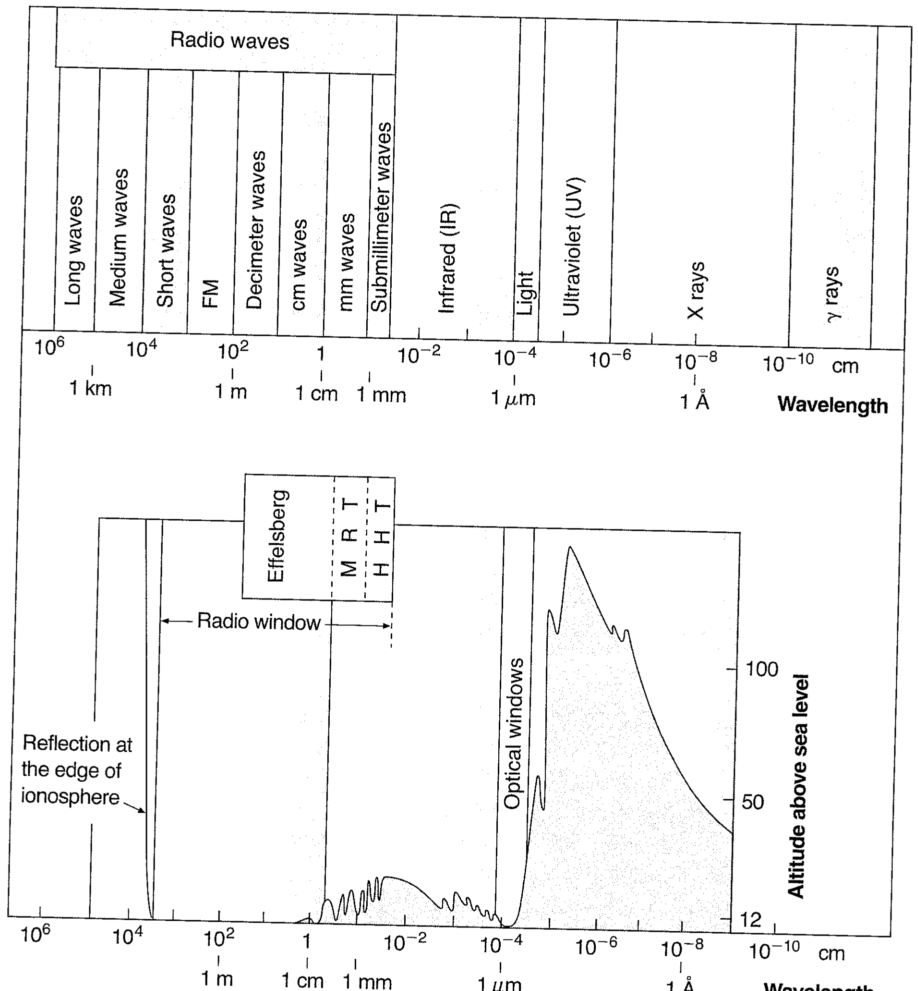

Figure 1.2

The wavelength regions of the electromagnetic spectrum (upper panel) and the altitude above sea level where this radiation can be detected. Most bands can only be observed from high-flying aircraft or space.
Figure based on *http://www.mpifr-bonn.mpg.de/div/hhertz/general_info4.html*

The following paragraphs outline observational aspects of various regions of the electromagnetic spectrum.

1.3.1 Ground Based Optical

Investigations in the optical spectral region have a long and rich history. Modern telescopes must be large to be competitive, since light gathering power is proportional

to the area of the primary mirror. Consortia of universities or countries have built most of today's new research facilities. The leading examples, with 8-m or larger telescopes, include at present the Keck Observatory, the United States' National Optical Astronomy Observatories (NOAO), and the European Southern Observatory (ESO).

Spectroscopic resolving powers up to 10^5 can often be achieved on moderately bright sources, and $\sim 10^3$ on faint ones. Spatial resolution is limited to just under $1''$ by atmospheric seeing. It can be partly overcome by adaptive optics, in which the optical surfaces of the telescope move to compensate for atmospheric distortions, but to date it has only been completely removed by observations from space.

Optical emission from nebulae include emission lines from warm ionized gas, and continua produced either by atomic processes in the nebula or by scattering of light from the photospheres of stars within it. Absorption lines are produced in the spectra of background stars or nebulae by ions or atoms of interstellar matter (ISM).

1.3.2 Ultraviolet

The vacuum ultraviolet ($912\text{Å} < \lambda < 3000\text{Å}$) can only be observed from space. Initially this spectral region was observed from high-altitude balloons and sounding rockets; today from long-lived orbital missions. The early successes of the Orbiting Astronomical Observatories (OAO) spacecraft, and the International Ultraviolet Explorer (IUE) were followed by the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Hubble Space Telescope (HST). HST may be able to operate through much of the decade 2000–2010 with more modest ultraviolet missions expected to follow it. HST is also highly competitive in the optical region because of the freedom from seeing, despite its modest aperture. Spatial resolution of $0.1''$ can be achieved routinely, and spectroscopic resolving powers similar to ground-based detectors (up to 10^5, but more typically 10^3–10^4) are possible.

Emission lines in the vacuum ultraviolet generally originate in higher-ionization species than the optical, and are produced in warm ionized gas. Interstellar matter (ISM) absorption lines from a broad range of species can also be found. Hotter stars and atomic processes in the emitting gas generally produce the continuum.

1.3.3 X-ray

X-rays have photon energies between 0.1 keV and 10 keV, corresponding to wavelengths between 100 Å and ~1 Å. (The region between the short-wavelength limit of the vacuum ultraviolet, 912 Å, and the long-wavelength limit of X-rays, 25 Å, is heavily absorbed by the ISM and hence is nearly unobservable.) Early observations were made from sounding rockets, but long-lived orbital missions, such as Uhuru, Einstein, ROSAT, ASCA, and at this writing Chandra and XMM, have had the greatest impact. Early missions were limited by the technology available then, and used small grazing incidence telescopes and proportional counting detectors. For instance, Einstein had two imagers, the Imaging Proportional Counter with $1'$ resolution and a High Resolution Imager with $3''$ resolution. The spectral resolving power of the HRI was between 10–50. The current missions have, for the first time, achieved resolutions similar to optical observations.

X-ray continuum sources are either very hot material, radiating thermal spectra, or very energy-rich material, radiating by non-thermal processes such as synchrotron emission. They are often coronae of "normal" stars or accreting material very near a collapsed object in AGN, cataclysmic binaries, or pulsars. Emission lines are often produced by atomic processes involving inner shells of heavy-element ions, and can come from a wide range of ionization.

1.3.4 Infrared

The infrared spectral region covers wavelengths between 1 μm and several hundred microns, although there is no agreed boundary between the far infrared and the submillimeter radio. Some wavelengths can be observed from the ground or from aircraft (Figure 1.2), while other wavelengths require high-altitude balloons or orbiting spacecraft. KAO, IRAS, and ISO were among the most prominent airborne and orbital missions. The lifetime of orbiting IR missions has been limited by the need to cool parts of the telescope and detectors cryogenically to very low temperatures, to minimize thermal emission. The resolution has been limited by technology to $\sim 1'$ and a resolving power between 10 and 1000. The infrared is the spectral region in which, with SOFIA, the Spitzer Space Telescope, and the James Webb Space Telescope, the greatest technical advances will take place over the next several years.

Cool thermal emission from grains, atomic processes in nebulae, and photospheres of cooler stars are efficient sources of IR continua. Emission lines from ions and atoms with a wide range of ionization potentials are observed, along with molecular rotational and vibrational transitions. Infrared light can penetrate through dusty regions more easily than optical light, making it possible to use the IR to detect otherwise heavily obscured objects.

1.3.5 Radio

Many radio wavelengths can be studied from the ground; such investigations date back to the mid-twentieth century. Very long waves are reflected by the Earth's ionosphere and can only be detected from orbit (Figure 1.2), while other radio waves are absorbed by water vapor in the atmosphere and can only be studied from dry mountain-top sites, such as the Atacama Large Millimeter Array (ALMA). Radio telescopes are often interferometers because the long wavelengths result in very poor diffraction limits for single-dish telescopes. The spectroscopic and spatial resolutions that are possible in the radio region are the very best; spatial resolutions of $10^{-3''}$ and resolving powers of over 10^5 are relatively routine.

1.3.6 Returned Data

In nearly all types of observing, digital data is returned from the telescope. Most observatories have software reduction packages specifically designed to handle data from their instrument. The final product may be an image or the emission-line fluxes or measures of the continuum at selected energies. Most missions produce large data archives that form a rich data set. These archives are now so extensive that many pilot projects can be carried out solely using them. Although the biggest discoveries will come from new observations, archival research is usually the first step in starting a large research program.

1.4 Physical Ideas

The source of energy that enables emission nebulae to radiate is, almost always, ultraviolet radiation from stars within or near the nebula. There are one or more hot stars, with effective surface temperature $T_* \geq 3 \times 10^4$ K, near or in almost every nebula; and the ultraviolet photons these stars emit transfer energy to the nebula by photoionization. In nebulae and in practically all astronomical objects, H is by far the most abundant element, and photoionization of H is thus the main energy-input mechanism. Photons with energy greater than 13.6 eV, the ionization potential of H, are absorbed in this process, and the excess energy of each absorbed photon over the ionization potential appears as kinetic energy of a newly liberated photoelectron. Collisions between electrons, and between electrons and ions, distribute this energy and maintain a Maxwellian velocity distribution with temperature T in the range 5,000 K $< T <$ 20,000 K in typical nebulae. Collisions between thermal electrons and ions excite the low-lying energy levels of the ions. Downward radiation transitions from these excited levels have very small transition probabilities, but at the low densities ($n_e \leq 10^4$ cm^{-3}) of typical nebulae, collisional deexcitation is even less probable; so almost every excitation leads to emission of a photon, and the nebula thus emits a forbidden-line spectrum that is quite difficult to excite under terrestrial laboratory conditions.

Thermal electrons are recaptured by the ions, and the degree of ionization at each point in the nebula is fixed by the equilibrium between photoionization and recapture. In nebulae in which the central star has an especially high temperature, T_*, the radiation field has a correspondingly high number of high-energy photons, and the nebular ionization is therefore high. In such nebulae collisionally excited lines up to [Ne V] and [Fe VII] may be observed, but the high ionization results from the high energy of the photons emitted by the star, and does not necessarily indicate a high nebular temperature T, defined by the kinetic energy of the free electrons.

In the recombination process, recaptures occur to excited levels, and the excited atoms thus formed then decay to lower and lower levels by radiative transitions, eventually ending in the ground level. In this process, line photons are emitted, and this is the origin of the H I Balmer- and Paschen-line spectra observed in all gaseous nebulae. Note that the recombination of H^+ gives rise to excited atoms of H^0 and thus leads to the emission of the H I spectrum. Likewise, He^+ recombines and emits the He I spectrum, and in the most highly ionized regions, He^{++} recombines and emits the He II spectrum, the strongest line in the ordinary observed region being λ4686. Much weaker recombination lines of C II, C III, C IV, and so on, are also emitted; however, the main excitation process responsible for the observed strengths of such lines with the same spin or multiplicity as the ground term is resonance fluorescence by photons, which is much less effective for H and He lines because the resonance lines of these more abundant elements have greater optical depth.

In addition to the bright-line and continuous spectra emitted by atomic processes, many nebulae also have an infrared continuous spectrum emitted by dust particles heated to a temperature of order 100 K by radiation derived originally from the central star.

Gaseous nebulae may be classified into two main types, diffuse nebulae or H II regions, and planetary nebulae. Though the physical processes in both types are quite similar, the two groups differ greatly in origin, mass, evolution, and age of typical members; so for some purposes it is convenient to discuss them separately. Nova shells are rare but interesting objects: tiny, rapidly expanding, cool photoionized nebulae. Supernova remnants, an even rarer class of objects, differ greatly from both diffuse and planetary nebulae. We will briefly examine each of these types of object, and then discuss Seyfert galaxies and other active galactic nuclei, in which much the same physical processes occur, although with differences in detail because considerably higher-energy photons are involved.

1.5 Diffuse Nebulae

Diffuse nebulae or H II regions are regions of interstellar gas (Figure 1.3) in which the exciting star or stars are O- or early B-type stars. Figure 1.3 is an example. They are young stars, which use up their nuclear energy quickly. Often there are several exciting stars, a multiple star, or a galactic cluster whose hottest two or three stars are the main sources of ionizing radiation. These hot, luminous stars undoubtedly formed fairly recently from interstellar matter that would otherwise be part of the same nebula they now ionize and thus illuminate. The effective temperatures of the stars are in the range 3×10^4 K $< T_* < 5 \times 10^4$ K; throughout the nebula, H is ionized, He is singly ionized, and other elements are mostly singly or doubly ionized. Typical densities in the ionized part of the nebula are of order 10 or 10^2 cm^{-3}, ranging to as high as 10^4 cm^{-3}, although undoubtedly small denser regions exist close to or even below the limit of resolvability. In many nebulae dense neutral condensations are scattered throughout the ionized volume. Internal motions occur in the gas with velocities of order 10 km s^{-1}, approximately the isothermal sound speed. Bright rims, knots, condensations, and so on, are apparent to the limit of resolution. The hot, ionized gas tends to expand into the cooler surrounding neutral gas, thus decreasing the density within the nebula and increasing the ionized volume. The outer edge of the nebula is surrounded by ionization fronts running out into the neutral gas.

The spectra of these "H II regions," as they are often called (because they contain mostly H$^+$), are strong in H I recombination lines and [N II] and [O II] collisionally excited lines, but the strengths of [O III] and [N II] lines may differ greatly, being stronger in the nebulae with higher central-star temperatures.

These H II regions are observed not only in our Galaxy but also in other nearby galaxies. The brightest H II regions can easily be seen on almost any large-scale images, but those taken in a narrow wavelength band in the red, including Hα and the [N II] lines, are especially effective in showing faint and often heavily

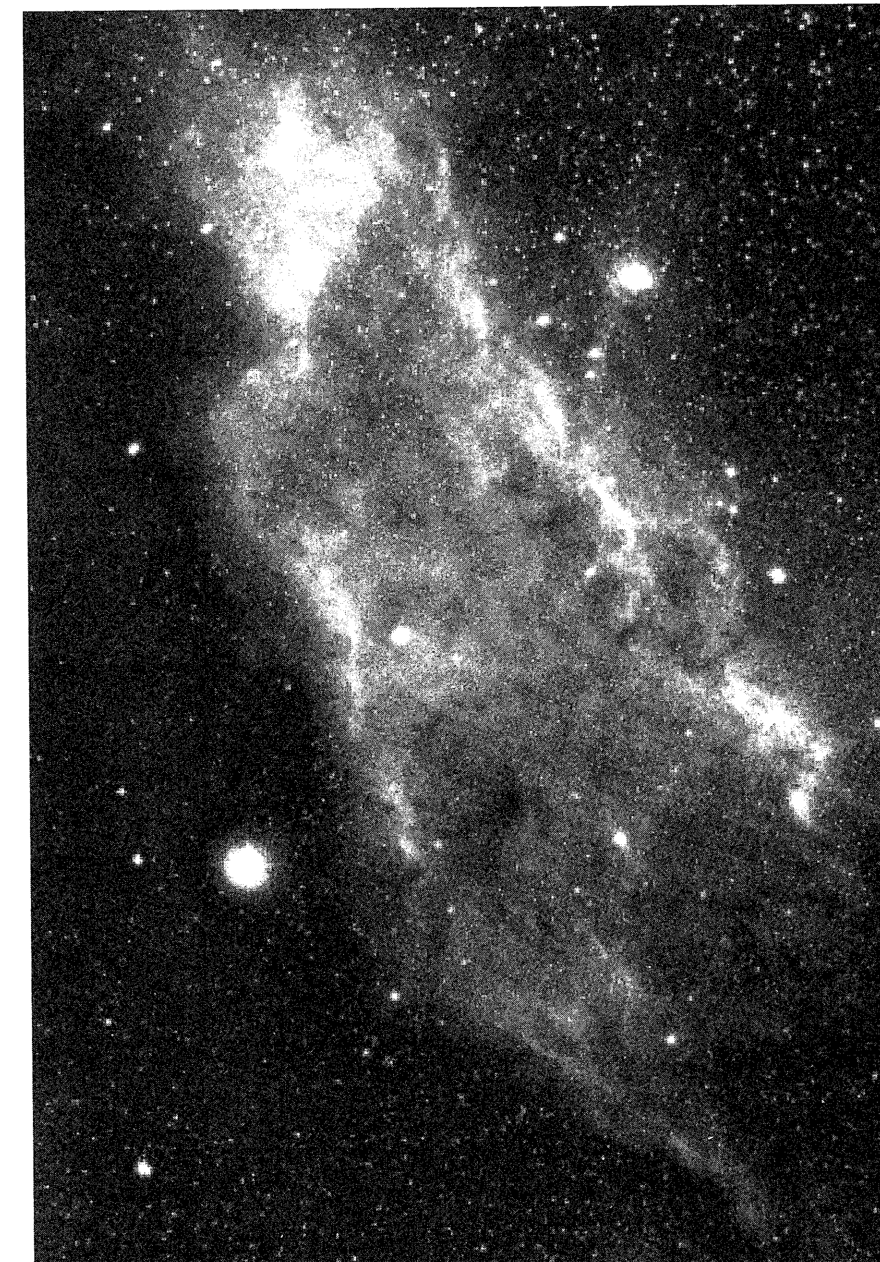

Figure 1.3
The H II region NGC 1499, also known as the California Nebula. The O star which photoionizes the gas, ξ Per, is off the picture to the right, just outside the bright emission nebula. (Photo © UC Regents/Lick Observatory)

reddened H II regions in other galaxies. The H II regions are strongly concentrated to the spiral arms, and indeed are the best objects for tracing the structure of spiral arms in distant galaxies. Radial-velocity measurements of H II regions then give information on the kinematics of Population I (young) objects in our own and other galaxies. Typical masses of observed H II regions are of order 10^2 to 10^4 $M_\odot$, with the lower limit depending largely on the sensitivity of the observational method used.

1.6 Planetary Nebulae

Planetary nebulae are isolated nebulae, often (but not always) possessing a fair degree of bilateral symmetry, that are actually shells of gas that have been lost in the fairly recent past by their central stars (Figure 1.4). The name "planetary" is purely historical and refers to the fact that some of the bright planetaries appear as small, disk-like, greenish objects in small telescopes. The central stars of planetary nebulae are old stars, typically with $T_* \approx 5 \times 10^4$ K, even hotter than galactic O stars, and often less luminous ($M_V = -3$ to $+5$). The stars are in fact rapidly evolving toward the white-dwarf stage, and the shells are expanding with velocities of order of several times the velocity of sound (25 km s^{-1} is a typical expansion velocity). However, because they are decreasing in density, their emission is decreasing, and on a cosmic time scale they rapidly become unobservable, with mean lifetimes as planetary nebulae of a few times 10^4 years.

As a consequence of the higher stellar temperatures of their exciting stars, typical planetary nebulae are generally more highly ionized than H II regions, often including large amounts of He^{++}. Their spectra thus include not only the H I and He I recombination lines, but often also the He II lines; the collisionally excited lines of [O III] and [Ne III] are characteristically stronger in their spectra than those in diffuse nebulae, and [Ne V] is often strong. There is a wide range in the temperatures of planetary–nebula central stars, however, and the lower-ionization planetaries have spectra that are quite similar to those of H II regions.

The space distribution and kinematic properties of planetary nebulae indicate that, on the cosmic time scale, they are fairly old objects, usually called old Disk Population or old Population I objects. This indicates that the bulk of the planetaries we now see, though relatively young as planetary nebulae, are actually near-terminal stages in the evolution of quite old stars.

Typical densities in observed planetary nebulae range from 10^4 cm^{-3} down to 10^2 cm^{-3}, and typical masses are of order 0.1 $M_\odot$ to 1.0 $M_\odot$. Many planetaries have been observed in other nearby galaxies, especially the Magellanic Clouds and M 31, but their luminosities are so much smaller than the luminosities of the brightest H II regions that they are more difficult to study in great detail. However, spectroscopic measurements of these planetaries give good information on velocities, abundances of the elements, and stellar evolution in these galaxies, and HST images show that they have forms quite similar to those of planetary nebulae in our Galaxy.

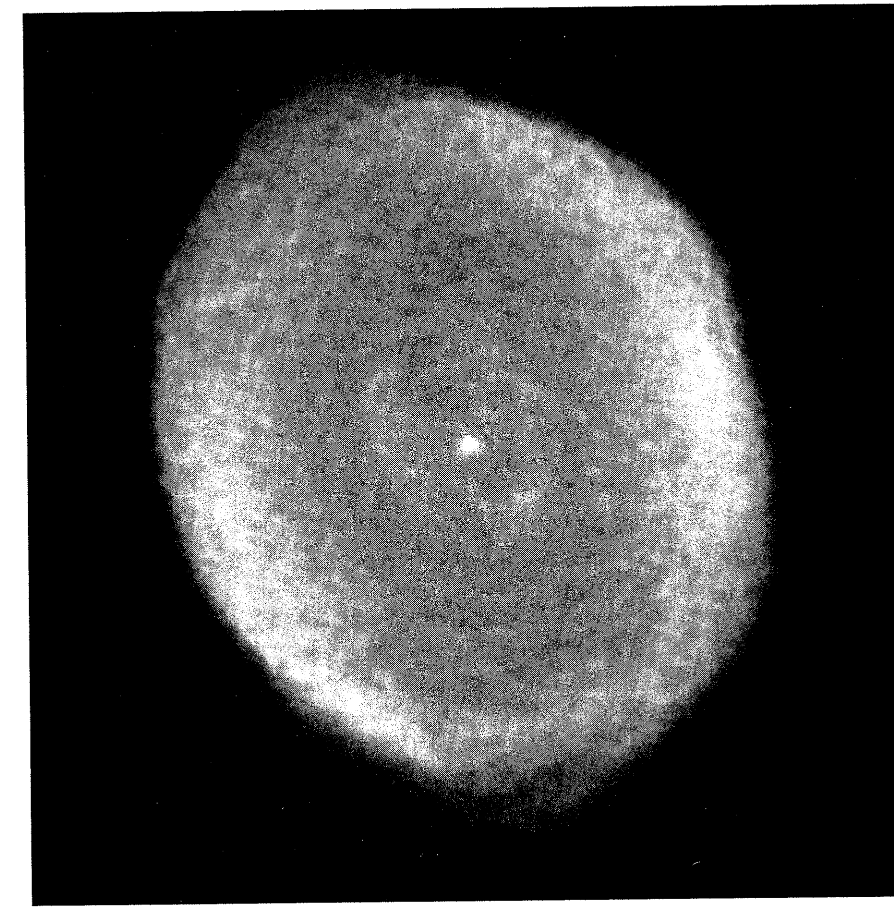

Figure 1.4
The planetary nebula IC 418. Note the fine structure, including the low narrow arc-like filaments, and the second smaller structure within the main nebula. (STScI)

1.7 Nova and Supernova Remnants

Many recent novae are surrounded by small, faint shells with emission-line spectra. As we shall see, they are tiny photoionized nebulae. A few emission nebulae are known to be supernova remnants. The Crab Nebula (NGC 1952), the remnant of the supernova of A.D. 1054, is the best known example, and small bits of scattered nebulosity are the observable remnants of the much more heavily reddened objects, Tycho's supernova of 1572 and Kepler's supernova of 1604. All three of these supernova remnants have strong non-thermal radio spectra, and several other filamentary nebulae with appearances quite unlike typical diffuse or planetary nebulae have been identified as older supernova remnants by the fact that they have similar non-thermal radio spectra. Two of the best known examples are the Cygnus Loop (NGC 6960–6992–6995) and IC 443. In the Crab Nebula, the non-thermal synchrotron spectrum observed in the radio-frequency region extends into the optical region, and extrapolation to the ultraviolet region indicates that this synchrotron radiation is probably the source of the photons that ionize the nebula. However, in the other supernova remnants no photoionization source is seen, and much of the energy is instead provided by the conversion of kinetic energy of motion into heat. In other words, the fast-moving filaments collide with ambient interstellar gas, and the energy thus released provides ionization and thermal energy, which later is partly radiated as recombination- and collisional-line radiation. Thus these supernova remnants are objects in which collisional ionization occurs, rather than photoionization. However, note that in all the nebulae, collisional excitation is caused by the thermal electrons that are energized either by photoionization or by collisional ionization.

1.8 Active Galactic Nuclei

Many galaxies, in addition to having H II regions and planetary nebulae, show characteristic nebular emission lines in the spectra of their nuclei. In most of these objects, the gas is evidently photoionized by hot stars in the nucleus, which is thus much like a giant H II region, or perhaps a cluster of many H II regions. The galactic nuclei with the strongest emission lines of this type are often called "extragalactic H II regions", "star-forming regions", or "starburst galaxies." Besides these objects, however, a small fraction of spiral galaxies have ionized gas in their nuclei that emits an emission-line spectrum with a wider range of ionization than any H II region. Usually the emission-line profiles show a significantly greater range of velocities than in starburst galaxies. These galaxies, totaling a few percent of all spiral galaxies, are called Seyfert galaxies. Many of the most luminous radio galaxies, typically N, cD, D, or E galaxies in form, have nuclei with very similar emission-line spectra. Quasars (quasistellar radio sources) and QSOs (quasistellar objects) are radio-loud and radio-quiet analogues of radio galaxies and Seyfert galaxies; they have similar optical spectra and even greater optical luminosities, but are much rarer in space. All these objects together are called active galactic nuclei. Among them are the most luminous objects in the universe, quasars and QSOs with redshifts up to $z \approx 6$, corresponding to recession velocities of more than $0.9c$.

Much if not all of the ionized gas in active galactic nuclei appears to be photoionized. However, the source of the ionizing radiation is not a hot star or stars. Instead, it is probably an extension to high energies of the blue "featureless continuum" observed in these objects in the optical spectral region. This is probably emitted by an accretion disk around a black hole, or by relativistic particles and perhaps a magnetic field associated with the immediate environs of the black hole. The spectrum of the ionizing radiation, whatever its source, certainly extends to much higher energies than the spectra of the hot stars that ionize H II regions and planetary nebulae. Also, the particle and energy densities are much larger in some ionized regions in active galactic nuclei than in nebulae.

1.9 Star Formation in Galaxies

Newly born stars "appear" in or near the interstellar matter from which they and their neighbors formed. Generally, when stars are formed under conditions we can observe in other galaxies, they do so in large numbers and some of them are O and B stars. These hot stars immediately begin photoionizing the residual ISM around themselves, creating large emission-line diffuse nebulae or huge regions of nebulosity. Thus we observe many star-forming regions (in nearby galaxies), or star-forming galaxies (more distant objects). The galaxies with the strongest nebular emission lines (such as Hβ or Hα or Pα or Brα) are called starburst galaxies, as unusually large numbers of stars are being formed within them within a short time interval.

The first survey of the infrared (5–500 μm) sky by the Infrared Astronomical Satellite (IRAS) discovered a class of galaxies that emit more energy in the infrared than in all the other pass bands combined. Previous optical surveys of galaxies had deduced a "luminosity function", a description of the fraction of that population that has various luminosities. From low to high luminosities, the range went from dwarf irregular galaxies like the Magellanic Clouds, to normal spiral galaxies like the Milky Way, to Seyfert galaxies (mostly early-type or distorted spirals), giant ellipticals, and quasars, which have the greatest luminosities we know. Among the spirals are many star-forming galaxies and fewer starburst ones. All of these sources radiate most of their energy in the optical passband. The infrared luminous sources discovered by IRAS were too faint to be included in optical surveys but are among the most luminous infrared sources in the sky. When these are included, it appears that most of the very most luminous galaxies ($L > 10^{11} L_\odot$) emit the majority of their luminosity in the infrared.

These infrared luminous galaxies are among the most luminous starburst galaxies. The infrared continuum that carries most of their luminosity is emitted by interstellar dust heated to 30–60 K by hot stars and by the emission lines they produce in the gas, creating a peak in the energy distribution near 60 μm. The underlying source of the great luminosity is a "super starburst", in which a large fraction of a galaxy's mass is involved in vigorous star formation. Interstellar dust then absorbs the energy emitted by the hot stars, which is eventually reradiated in the infrared. The observations can be understood if a very large fraction of a galaxy's mass, $\sim 10^{10}\ M_\odot$, is quickly converted into stars in a dusty environment.

The starburst phenomenon is thought to be the result of interactions and mergers of gas-rich spirals. The host galaxies tend to show signs of interacting with other galaxies or of being an otherwise disturbed system. During such galactic collisions some of the gas in the ISM loses its angular momentum and quickly falls towards the merger nuclei. Models suggest that as much as $10^{10}\ M_\odot$ of gas and dust can build up within a few hundred parsecs of the center, resulting in vigorous star formation. Most of this star formation occurs in regions that are heavily obscured by dust, so many parts of the system can only be observed directly in the infrared. For this reason it is necessary to develop emission line diagnostics that use only infrared lines, the subject of a later chapter.

The basic physical principles that govern the structures and emitted spectra of active galactic nuclei are largely the same as those that apply in H II regions and planetary nebulae. However, because of the large proportion of high-energy photons in the ionizing flux, some new physical processes become important in active galactic nuclei, and these cause their structures to differ in important details from those of classical nebulae. These differences can best be analyzed after H II regions and planetary nebulae are well understood. Hence we treat nova shells, supernova remnants, and active galactic nuclei in the final chapters of this book.

References

General reviews on astronomical research are found in a variety of places. Three of the best series are

Annual Reviews of Astronomy and Astrophysics, by Annual Reviews Inc. These come out once per year and feature articles on a variety of research topics.

Astronomical Society of the Pacific Conference Series, by the Astronomical Society of the Pacific. Each book of this series summarizes a specialist conference on a chosen topic, many of them organized by the International Astronomical Union. The articles are a mix of longer reviews and shorter research summaries.

The Saas Fe Conference Series. These are the proceedings from summer schools held each year. Each book is on a chosen topic and features a few longer articles.

A brief historical sketch of the development of nebular astrophysics is contained in an article on "pioneer nebular theorists" (which also includes some of the main observational results on which they built):

Osterbrock, D. E. 2001, Revista Mexicana de Astronomia, Serie d. Conferencias, 12, 1 (in English).

The following are on-line data bases of astronomical sources. At this time most archives are limited to space-based data, but archives of ground-based are being developed. The main archives at the time of this writing are

ADS, the NASA Astrophysics Data System, has links to much of the published astronomical literature. http://adsabs.harvard.edu/

HEASARC, the High Energy Astrophysics Science Archive Research Center, is "a source of gamma-ray, X-ray, and extreme ultraviolet observations of cosmic (non-solar) sources". http://heasarc.gsfc.nasa.gov/

SIMBAD, a database operated at CDS, France. This "brings together basic data, cross-identifications, observational measurements, and bibliography, for celestial objects outside the solar system: stars, galaxies, and non-stellar objects within our galaxy, or in external galaxies". http://cdsweb.u-strasbg.fr/Simbad.html

The Hubble Data Archive provides access to data obtained with the Hubble Space Telescope. http://archive.stsci.edu/

MAST, the Multi-mission Archive at STScI, provides access to data from a variety of missions ranging from the extreme UV through near IR. http://archive.stsci.edu/mast.html

IPAC, the Infrared Processing and Analysis Center, has access to NASA's infrared program. http://www.ipac.caltech.edu/

NED, the NASA/IPAC Extragalactic Database at JPL, can be searched by object name, type of data, literature, or tools. http://nedwww.ipac.caltech.edu/

Additionally, meta-archives, collections of links to individual archives, are being developed. A good one is

Canadian Astronomy Data Centre, at http://cadcwww.hia.nrc.ca/

The following gives an overview of various ways to find information in these databases:

Skiff, Brian A. 2002, Sky & Telescope, 103, 50.