2
Starburst Galaxies

Summary

- The main types of active galaxy – starburst and AGN.
- The distinguishing properties of starburst galaxies.
- How starburst galaxies are detected – infrared, ultraviolet and emission line searches.
- The formation of starburst galaxies and their energy sources – buried quasars, star-forming regions, galaxy collisions and mergers.
- Starburst lifetimes.
- Boxes
  Star formation, young stars and spiral arms
  H II regions

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The classification of stars
Gravitational lensing
Thermal radiation.

2.1 Recognizing Starburst Galaxies

Active galaxies take two differing forms – those whose spectra are dominated by radiation from recently formed stars, either seen directly or inferred after the stars' radiation has been absorbed and re-emitted at different wavelengths, and galaxies whose spectra are dominated by non-stellar energy sources (often called non-thermal radiation – Box 3.1). Many astronomers regard the latter type as being the "real" active galaxies and take little interest in the first type. Nonetheless the first type, that goes by the generic name of starburst galaxies, undoubtedly have more going on inside them than classical galaxies, and so are worthy of inclusion in the group, furthermore the second type of active galaxy often has starburst activity occurring as well as its non-thermal emissions. The second type of active galaxies are generally called active galactic nuclei (AGNs), because most of the activity usually occurs close to the center of the galaxies' cores. AGNs are discussed in Chap. 3, *et seq.*; here we are concerned with the starburst group.

A starburst galaxy is one that is experiencing a torrent of star formation far more intense than that found amongst the classical or normal galaxies. There is no sharp division however between classical and starburst galaxies – star-forming activity in galaxies varies more or less smoothly from galaxies with rates far less than that of the Milky Way to that of the most violent starburst galaxies.

Given that there is no sharp transition between classical and starburst galaxies, recognizing to which of the types a particular galaxy belongs is not a precise process. Several criteria can be used to refine the choice, but in the borderline region one might as well toss a coin. Firstly, starbursts usually, but not always, occur towards the center of the galaxy. Secondly, the starburst region is small compared with the

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size of the galaxy – typically less than 10% of its size or under 3,000 ly (1,000 pc) and with much of the activity occurring in numerous much smaller regions each a few tens of light years across (~10 pc) that have luminosities up to 100 million times that of the Sun. The energy emitted by the massive stars in these regions dominates the emission from the whole galaxy (Box 2.1) especially for the most energetic galaxies. Thirdly, the rate of star formation greatly exceeds the rate sustainable over the galaxy's lifetime, so that the starburst event must be a relatively transient episode. A classical galaxy like our own has a star-formation rate within the disk of a few solar masses per year, equivalent to perhaps 100 actual new stars since low-mass stars are far more common than those with high masses; the star-formation rate in a starburst galaxy can up to a thousand times higher than this. The starburst is usually formed from a large number of smaller star-forming regions and some of these will have progressed to the H II region stage (Box 2.2). The spectrum of a starburst galaxy thus shows the emission lines characteristic of H II regions as well as the normal absorption-line spectrum of a classical galaxy – in fact an alternative name for a starburst galaxy is H II galaxy. The emission lines in the visual region are principally due to neutral hydrogen and helium plus forbidden lines (Box 1.1) from singly ionized oxygen and nitrogen and doubly ionized oxygen and neon. Several of these lines may also be present in the spectra of the AGN type of active galaxies but the latter can be distinguished from starburst galaxies because at least some of their emission lines will be considerably broader than either the emission or absorption lines of starburst and classical galaxies.

The rate of star formation within starburst galaxies is so high that a quarter of all high-mass stars in the local universe[6] originate within

[6]This is not the same as the local cluster of galaxies that includes the Milky Way Galaxy and M 31, but is a somewhat ill-defined region over which conditions are roughly similar to those closer to the Milky Way. It probably extends out to a redshift of one, i.e. to a distance of approximately 8,000 Mly (2,500 Mpc).

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them. It is likely that they also produce many of the lower mass stars, but these are too faint to detect and so that cannot be confirmed observationally. During the early stages of the universe the contribution of starbursts to the overall production of stars may have been even higher. The extreme luminosities of high-mass stars (Box 2.1) mean that about a tenth of all the energy produced within the local universe comes from starburst regions.

The energy from starbursts, particularly that coming from stellar winds and supernovae, heats the interstellar gas. The hot gas then expands outwards along the lines of least resistance, which will usually be perpendicular to the galaxy's disk. The resulting galactic winds can reach temperatures of several million kelvin, and speeds of up to a thousand kilometers per second. In many cases the wind will produce low-density bubbles up to 100,000 ly (30 kpc) across on either side of the starburst galaxy that can be detected by their x-ray emissions. It is probable that the material in galactic winds from starburst galaxies eventually merges with the intergalactic medium and is the source of the elements heavier than hydrogen and helium that are to be found there.

Starburst galaxies are located at all distances, implying that they have been formed throughout most of the life of the universe. Some, like M 82 at 11 Mly (3.3 Mpc) away from us, are nearby, and so their starburst activity is continuing at the current time. Other starburst galaxies may be found that were in existence just 1.5 aeons after the Big Bang – i.e. at distances up to 12,000 Mly (3,500 Mpc) and when perhaps one galaxy in eight contained a powerful starburst. The nearest starburst galaxy is NGC 253, which is just 8–10 Mly (3 Mpc) away from us.

Box 2.1 Star Formation, Young Stars and Spiral Arms

Anyone looking at images of spiral galaxies might well come to the conclusion that the material in the disk of the galaxy is concentrated into the arms. In fact the density of the disk is relatively uniform, there is only a slight increase in the density in the regions occupied

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by the arms. The reason why the arms stand out so sharply from the rest of the disk is that they contain numerous star-forming regions. In those regions the massive hot young stars are extremely bright and outshine the far more numerous less massive stars. Few star-forming regions are to be found in the remainder of the disk and so, despite there still being many stars in those regions, they appear dark in comparison with the arms.

Most stars are formed inside giant molecular clouds (GMCs). GMCs are the largest single structures found in the Galaxy, yet they have only been discovered relatively recently. Their obscurity is due to their temperatures that can be as low as 10 K (−263°C). They radiate therefore mainly in the far infrared and microwave regions of the spectrum and so their study had to await the development of suitable detectors and telescopes for those regions. GMCs can be up to 300 ly (100 pc) in size and contain between a few hundred thousand and ten million solar masses of material. About 1% of a GMC's mass is in the form of dust and so sometimes they can also be detected as dark absorbing regions. They contain, as their name suggests, a large number of different molecules many of which are organic (but produced "naturally" not as the result of the actions of living organisms). The average density of a GMC is around a billion molecules and atoms per cubic meter – for comparison our atmosphere is some 100,000 trillion times thicker than this at sea level. Within the GMC are denser regions where the numbers of particles per cubic meter can be a hundred or a thousand times the average. The Galaxy contains at least 3,000 GMCs, the nearest being in Orion and about 1,500 ly (500 pc) away from us (Fig 2.1). The visible Orion nebula (M 42, Fig 2.1) is a small part of the whole Orion GMC that has been heated to high temperatures by the hot stars inside it.

The low temperatures and relatively high concentrations of the material in the denser regions of GMCs lead to the gravitationally induced collapse of the region. Eventually that collapse produces new stars. Currently there are two models for how this may occur. In the first of these, called "gravitational collapse and fragmentation",

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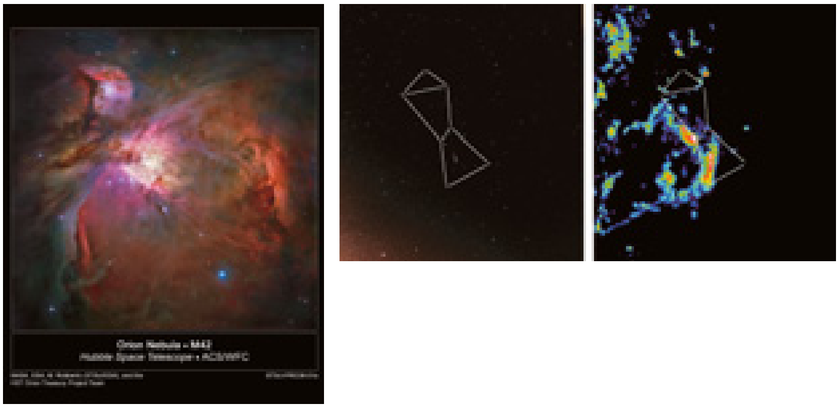

Figure 2.1 The Orion Nebula (M 42) (Left: Image courtesy of NASA, ESA, M. Robberto (STScI/ESA) and the Hubble space telescope Orion treasury project team) that is a small part of the whole Orion Giant Molecular Cloud (Right: Image courtesy of Thomas Dame, Harvard-Smithsonian Center for Astrophysics).

the collapsing clumps are large and they fragment during the infall so that many binary and multiple stars result. The second theory, "competitive accretion", has several centers, each about 1 ly (0.3 pc) across, developing within the clumps as they collapse. The centers themselves then collapse under gravity and build up their masses by accreting material from the larger surrounding clump.

Whichever of these processes is correct – and they both could be – the final result is the formation of a group of stars deep inside the remainder of the dense core of the GMC. Up to this point little of the process is observable. Now however the stars heat the dust in the surrounding material until it is hot enough to emit infrared radiation. The GMC is largely transparent at infrared wavelengths and so the young stars appear as infrared sources within the GMC. Later the energy from the stars is sufficient to heat and drive off the remainder of the GMC, and the stars become directly visible to visual observers. The hot gas before it is lost completely forms an H II

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region, which is a gaseous nebula with an emission-line spectrum (Box 2.2). H II regions are some of the most spectacular sights in the sky – rivalling galaxies – and the well-known Orion Nebula (M 42, Fig. 2.1) is exactly just such a region that has developed on the nearest side to us of the Orion GMC.

The young stars, that can now be seen directly, have masses ranging from 0.08 solar masses (the brown dwarf limit) to slightly over 100 solar masses (beyond which stars become unstable). By far the majority of stars though are at the low-mass end of this range – 80% have masses less than that of the Sun. The higher mass stars are thus few and far between, but their brightnesses are out of all proportion greater than those of the lower mass stars – a star with a mass half that of the Sun will have a luminosity about 3% that of the Sun, while a five solar-mass star will be 600 times brighter and a 50 solar-mass star 200,000 times brighter than the Sun. The emission from the star cluster will thus be completely dominated by the few high-mass stars within it. As well as high luminosities the large stars also have high surface temperatures. Their emitted radiation is thus predominantly in the ultraviolet and blue regions of the spectrum. The ultraviolet radiation ionizes the surrounding gas, producing the H II region, while the blue emission produces the bluish tinge detectable for the spiral arms on color images.

The enormous luminosity of the young massive stars means that they consume the hydrogen available as fuel for nuclear reactions much more rapidly than the more frugal lower mass stars. A 50-solar mass star will run out of hydrogen in around two and a half million years, compared with 10 billion years for the Sun. The stars in the Orion nebula are about one million years old. The hottest of the stars forming the Trapezium at the center of the nebula has a mass of about 60 solar masses and a luminosity some 300,000 times that of the Sun and it is thus now about halfway through its life. Soon (in astrophysical terms) after the birth of a group of stars therefore, the high-mass members will come to the ends of their lives and fade away or explode as supernovae and disappear. Since those massive stars have dominated the emission from the star-forming region, as their luminosities diminish, so also will that of the star-forming region.

The spiral arms of galaxies are thus seen as such because the formation of stars is triggered at their leading edges, perhaps by a density wave or some other process. After a few million or tens of millions of years the massive stars die and the star-forming regions disappear from our sight, so that the spiral arm seems to fade away at its trailing edge. The majority of the stars produced within the star-forming-region – those with the lower masses – are still however in existence and continuing to radiate, but are too faint to be detectable across cosmological distances. The general density within the disk of the galaxy is thus reasonably uniform with only a slight enhancement near the visible spiral arms.

Box 2.2 H II Regions

Stars of spectral classes O and B (Box 2.3) have very high surface temperatures and emit a great deal of ultraviolet radiation. The lives of such stars are short (Box 2.1) and so they are usually still to be seen in the groups where they were produced by the star-forming region, along with many cooler, lower mass stars. The ultraviolet photons from the few hot stars in such a group have enough energy to ionize many of the atoms in the gas surrounding it. A bubble of very hot (10,000 K) gas, which is almost completely ionized in its inner regions, thus surrounds the group of stars. The bubble is called an H II region because the hydrogen within it is almost completely ionized, and the symbol for ionized hydrogen is H II (Box 1.1). The Orion nebula (M42, Fig. 2.1) is a relatively nearby H II region.

Within the hot bubble, the ions and electrons will be moving around rapidly and will undergo frequent collisions. During such

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collisions it is possible for the electron to bond with the ion (known as recombination) to produce the neutral atom again (or a lower stage of ionization). The electron's energy will be released in the form of photons belonging to some of the characteristic spectrum lines of that atom or ion. H II regions thus have emission-line spectra (Fig 1.3) and the strongest lines in the visual spectrum are usually due to hydrogen (H I 388.9, H I 397.0, H I 410.1, H I 434.0, H I 486.1, H I 656.3), helium (He I 388.8, He I 447.1), nitrogen ([N II] 575.5, [N II] 654.8, [N II] 658.3), oxygen ([O II] 372.7, [O III] 495.1, [O III] 500.7) and neon ([Ne III] 386.9).

When a starburst region is directly visible, it is the O and B stars plus the H II regions that provide the bulk of the emitted radiation. Similarly it is principally these stars and nebulae that cause the spiral arms of classical galaxies to stand out within the galaxies' disks (Chap. 1).

Box 2.3 The Classification of Stars

A useful and widely used classification system for stars is based upon their surface temperatures and is known as a star's spectral type. For historical reasons the labeling of the spectral type is illogical and inconvenient, however it seems unlikely to be changed now, so the reader of necessity has to come to terms with it. Refinements and additions have been added in recent years, but for the purposes of this book, the basic system will suffice.

The classification is based upon the stars' surface temperatures, but these are not measured directly. Instead the varying appearances of the visual spectra of stars with differing surface temperatures are used and the class determined from the presence or absence of certain spectrum lines or from the changing relative intensities between pairs of spectrum lines (hence "spectral type"). There are seven major

Table 2.1 Stellar spectral types and surface temperatures.[7]

Spectral type	Surface temperature (K)	Surface temperature (°C)	Surface temperature (°F)
O5	42,000	42,000	76,000
B0	30,000	30,000	54,000
B5	15,200	15,000	27,000
A0	9,790	9,520	17,200
A5	8,180	7,910	14,300
F0	7,300	7,030	12,700
F5	6,650	6,380	11,500
G0	5,940	5,670	10,200
G5	5,560	5,290	9,550
K0	5,150	4,880	8,820
K5	4,410	4,140	7,480
M0	3,840	3,570	6,460
M5	3,170	2,900	5,250

classes indicated by upper case letters, which in order of decreasing temperature are:

O B A F G K M

As previously mentioned, the inconvenient labels arose historically. The reader may however find the following mnemonic useful:

Oh Be A Fine Girl/Guy Kiss Me

Each of these major classes is sub-divided into 10, with each sub-division labeled by a number from 0 to 9. The Sun thus has a spectral class of G2; Sirius (α CMa) is A1 while Antares (α Sco) is M2. The hottest stars known at the moment are O3, while at the cool end, the sequence can be continued beyond M9 into the brown dwarfs. The relationship between surface temperature and spectral class is given in Table 2.1.

[7]These are the values for solar-type stars, usually called main-sequence stars. Slightly different temperatures are found for larger stars (giants and supergiants) of the same spectral class.

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Additionally, the brightness of a star can often be estimated from its spectrum and so a luminosity classification is frequently added to the spectral class. The brighter stars with a given surface temperature (i.e. spectral type) are clearly larger than fainter stars of the same temperature – their emissions per unit area are the same, so the brighter stars must have larger surface areas than the fainter ones. The luminosity classification is thus also a size classification. A Roman numeral from I to VII is used for the luminosity class (Table 2.2):

Table 2.2 Stellar luminosity classes.

Luminosity class	Luminosity for spectral type G5 ($L_{\odot}$)	Star type
I	~23,000	Supergiant
II	~1,000	Bright giant
III	~33	Giant
IV	~5	Subgiant
V	~0.7	Dwarf (also called main-sequence stars – these are the commonest stars by far, and the class to which the Sun belongs).
VI	~0.2	Subdwarf
VII	~0.0001[8]	White dwarf.

The luminosity class is added to the spectral type so that the Sun becomes G2 V, Sirius, A1 V while Antares is M2 I.

[8]White dwarfs have a separate classification system from the normal spectral type. This is the luminosity for a white dwarf with a surface temperature similar to that of a G5 star. Most white dwarfs however have much higher temperatures than this.

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2.2 Finding Starburst Galaxies

H II regions and hot O and B stars can be seen within the images of many galaxies by direct visual inspection, and galaxies with numerous such indicators of star-forming regions have long been identified – the Mice (Fig. 1.9) and M 82 (Fig. 2.2) for example. Until the launch of the Infrared Astronomy Satellite (IRAS) in 1983 however, the number of galaxies known to have such unusually vigorous rates of star formation was small. IRAS' mission was to survey the sky at infrared wavelengths and during its 10 months of operation – its lifetime was limited by the amount of liquid helium that it could carry to cool its telescope and detectors – it observed over 20,000 galaxies as well as more than 200,000 stars and other objects. The most outstanding discovery that came from IRAS' data however was of a new class of galaxies that

Figure 2.2 An HST image of the starburst galaxy, M 82. (Image courtesy of NASA, ESA, R. de Grijs (Institute of Astronomy, Cambridge, UK).)

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emitted huge amounts of energy in the far infrared. The infrared energy emitted by these galaxies may originate from star-forming regions and in many instances greatly exceeds the total energy coming from normal large galaxies. These galaxies have become known by several names – IRAS galaxies, H II region galaxies, Far Infrared Galaxies (FIRGs), super starburst galaxies and Ultraluminous Infrared Galaxies (ULIRGs) as well as starburst galaxies. More recently SCUBA galaxies (for the Sub-millimeter Common User Bolometer Array that is used on the James Clerk Maxwell telescope) and sub-millimeter galaxies have been added to the pantheon for those galaxies whose energy is mainly found at even longer wavelengths than the far infrared. Some of these names may be synonyms, but it seems likely that more than just rapid star formation is needed to explain all the phenomena (Sect. 2.3, Chap. 3, *et seq.*).

Other than through infrared surveys – and IRAS has been followed by later infrared spacecraft such as ISO (Infrared Space Observatory) and Spitzer – starburst galaxies are mainly discovered via two of their other properties. The massive stars in star-forming regions emit much of their energy at ultraviolet wavelengths, so starburst galaxies may be identified from their high ultraviolet emissions. The ultraviolet photons also ionize atoms and the subsequent recombination of ions and electrons produces emission lines at visual wavelengths (Box 2.3). In this way in the 1960s and 1970s, surveys conducted by Benjamin Markarian using the 1.3-m Schmidt camera at the Byurakan observatory and looking for galaxies with near ultraviolet excesses and/or emission lines found over 1,500 examples. Out of these Markarian galaxies around 90% proved to be starburst galaxies while the remainder were mostly Seyfert galaxies (Chap. 3).

The brightest starburst galaxies are the ULIRGs and these may be the brightest objects in the universe (they may though not be true starburst galaxies; see Sect. 2.3). ULIRGs all have far infrared brightnesses that exceed a trillion solar luminosities. For comparison, quasars and QSOs (Chap. 3, *et seq.*) can have total brightnesses up to ten trillion solar luminosities. At least one ULIRG, however, may out-do even the quasars. FSC 10214+4724[9], an IRAS galaxy that is also known as the Rowan-Robinson galaxy after its discoverer Michael Rowan-Robinson, is some 11,500 Mly (3,500 Mpc) away from us. Its apparent far infrared luminosity is an incredible 300 trillion times that of the Sun – perhaps 30 times brighter than the brightest quasar. There is some evidence though that the apparent brightness of FSC 10214+4724 may have been enhanced, perhaps by as much as a factor of 10, by gravitational lensing (Box 2.4), so that its true luminosity is much less than $3 \times 10^{14}\,L_{\odot}$. It must remain, however, a strong candidate for being the brightest object in the visible universe.

Box 2.4 Gravitational Lensing

Sir Arthur Eddington undertook one of the earliest observational tests of Albert Einstein's theory of general relativity in 1919. Einstein had predicted that gravitational fields would deflect the paths of light beams. Light (or other e-m radiation) skimming the surface of the Sun should thus have its direction of travel changed slightly by the Sun's gravitational field and the object from whence the light originated should appear to be in a slightly different part of the sky. Eddington observed the solar eclipse of 1919 to see if the positions of stars then behind the Sun were moved compared with their positions when the Sun was not in that region. He found that they were moved and by just the amount required by general relativity.

[9]FSC stands for the IRAS Faint Source Catalogue. The numbers give the object's right ascension and declination: RA = 10 h 21.4 m, Dec = +47°24′. With the huge numbers of stars, nebulae, galaxies, etc. that the HST and other space observatories have identified plus contributions from ground-based surveys like the Sloan Digital Sky Survey (SDSS), using names such as "Whirlpool" galaxy or catalogue numbers such as "NGC 1275" has become impractical. This type of positional designation is thus now very widely used for objects of many types.

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A gravitational field can thus deflect the paths of light beams passing through it. Now deflecting the paths of light beams is exactly what a lens does. However for a converging lens, the amount of the deflection increases the further away the light beam passes from the center of the lens (Fig. 2.3). For the Sun, or any other object where the light passes by beyond its outer limits, the gravitational field weakens away from the object and so the gravitational deflection decreases outwards (Fig. 2.3). The gravitational "lens" thus does not

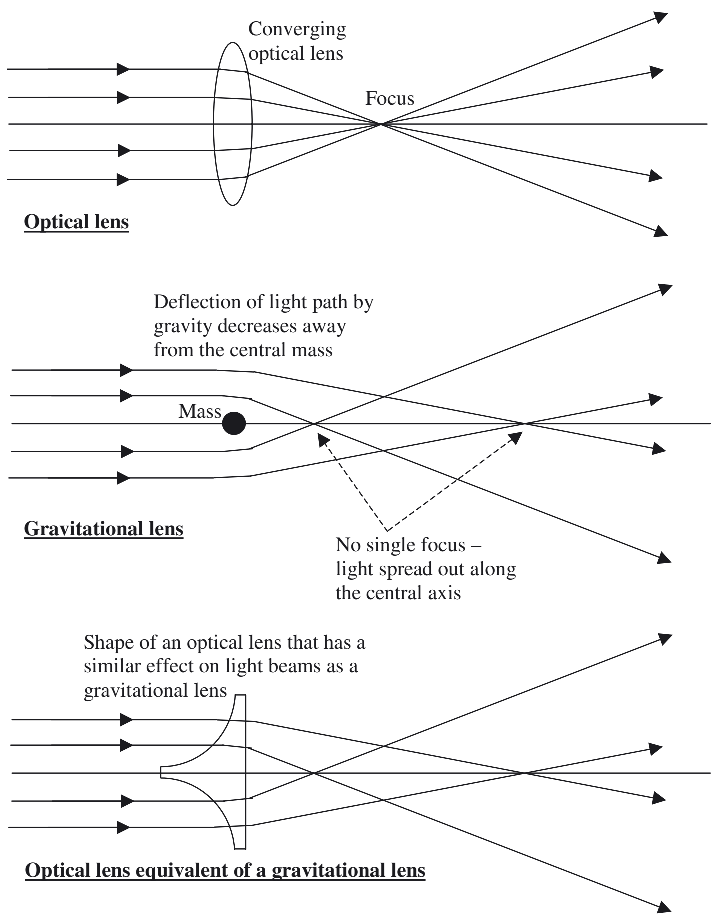

Figure 2.3 Optical and gravitational lenses.

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produce an image in the manner of a converging optical lens; instead its optical equivalent would be like the stem and base of a wine glass (Fig. 2.3). In both cases no image is produced, but light from the distant object is concentrated along the central axis. To an observer on or close to the central axis the distant object would thus appear brighter than if the lensing mass were not present.

A gravitational lens does not produce a true image, but if the distant object, the lens and the observer are almost exactly aligned, then the light from the distant object will be spread out into a ring centered on the lensing object (usually a galaxy). Such rings are known as Einstein rings, and although the chances of the observer being in the right position are very small, several such rings have been found.

Much more frequently the observer is close to but not on the central axis of the gravitational lens. The Einstein ring then breaks up into one or more arcs or more distorted shapes or into several point sources. In the latter case it is possible to get four point images at the corners of a square and the effect is then known as an Einstein cross.

2.3 The Origins of Starburst Galaxies

The far infrared emissions from FIRGs and ULIRGs, etc. originate as radiation from hot dust particles (thermal emission; see Box 2.5). In most cases the starburst regions are not seen directly, but their existence is inferred as the sources of the energy that heats the dust. Since the energy source is not seen directly, it is possible that for some of these galaxies it is not a starburst region. In particular some ULIRGs have broader emission lines than most other starburst and normal galaxies – and broad emission lines are a characteristic of the AGN type of active galaxy (Chap. 3, *et seq.*). An alternative model for some ULIRGs is thus

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that of a buried quasar. The quasar is deeply hidden inside a dense region of molecular gas and dust whose mass may amount to ten billion times that of the Sun. The quasar gives no indication of its presence except in the one or two galaxies where a small amount of its radiation leaks out. The energy from the quasar goes to heat the dust, which then re-radiates at far infrared wavelengths just as though a starburst region had heated it. To add to the confusion however, it is quite possible that ULIRGs containing buried quasars also contain starburst regions. Recent results from the ISO spacecraft suggest that about a quarter of the observed ULIRGS are powered by hidden quasars while infrared spectroscopic observations from the European Southern Observatory's (ESO) Very Large Telescope (VLT) imply that two-thirds of ULIRGs contain AGNs although only in a third of these does the AGN contribute significantly to the overall luminosity.

Box 2.5 Thermal Radiation

The spectrum of a hot solid, liquid or dense gas is a continuous one (Box 1.1) but the emission does not occur equally at all wavelengths. There is a wavelength at which the emitted energy peaks and the intensity then drops off rapidly towards shorter wavelengths, and somewhat more slowly towards longer wavelengths. The wavelength of the peak intensity becomes shorter as the temperature of the emitting body rises. This is a matter of common experience in that a heated object initially glows a deep red, then becomes yellow and eventually white as it gets hotter. The wavelength of the peak emission for a wider temperature range is given in Table 2.3.

GMCs, whose temperatures are less than 100 K, thus emit energy at far infrared/sub-millimeter wavelengths, the dust involved in infrared galaxies has temperatures ranging from less than one hundred to a few hundred K so that their peak emissions occur in

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Table 2.3 Thermal radiation peak emission wavelengths.

Temperature (K)	Wavelength of the peak emission intensity	Part of the spectrum	Example
10	300 μm	Far infrared/sub-millimeter	MWBR (2.7 K)
20	150 μm	Far infrared	
50	60 μm	Far infrared	
100	30 μm	Mid-infrared	Dust in GMCs
200	15 μm	Mid-infrared	Earth (300 K)
500	6 μm	Near infrared	
1,000	3 μm	Near infrared	Heated interstellar dust
2,000	1.5 μm	Near infrared	
5,000	600 nm	Visual	Sun
10,000	300 nm	Near ultraviolet	
20,000	150 nm	Ultraviolet	
50,000	60 nm	Ultraviolet	O-type star
100,000	30 nm	Extreme ultraviolet	
200,000	15 nm	Extreme ultraviolet	
500,000	6 nm	Soft x-ray	
1,000,000	3 nm	Soft x-ray	Solar corona
2.000,000	1.5 nm	X-ray	
5,000,000	600 pm	X-ray	Starburst winds
10,000,000	300 pm	X-ray	

the far to near infrared, the Sun at almost 6,000 K emits primarily in the visual region, while the galactic winds from starburst galaxies reach temperatures of millions of degrees and so are detectable at x-ray wavelengths.

With most, perhaps three-quarters, of the starburst galaxies, however, it is vigorous star formation that leads to their unusual properties and behaviors. Almost all starburst galaxies – including even those ULIRGs that might contain buried quasars – show signs of undergoing or of having recently undergone an encounter with another galaxy. In clusters of galaxies the separations between individual galaxies even today are typically only around 10–100 times the sizes of the galaxies. In the past, since the universe is expanding, the relative separations would have been

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much smaller. A large cluster of galaxies is thus in much the same situation as a thousand jumbo jets that have all to fly at the same time and remain within the same cubic mile of the atmosphere. Collisions would be inevitable – the more so because within the cluster, gravity is pulling the individual galaxies towards each other the whole time.

A collision between two galaxies though is quite different from a collision between two aircraft. The stars within the galaxies are separated by enormous distances compared with their diameters, so that they simply pass each other by. A few stars may have encounters sufficiently close to change their trajectories by significant amounts, but it is unlikely that any two stars will actually hit each other. The gravitational fields of the galaxies as a whole though will alter the paths of most of the stars in both galaxies. These tidal forces can result in the formation of many strange structures such as double nuclei; the long tails seen in the Mice (Fig 1.9) and even produce ring galaxies such as Hoag's object (Fig. 1.9).

The situation is different however, for the gas and dust clouds within the galaxies, these will actually hit each other. The outcome of the collision will then depend upon the details of the encounter – one galaxy may be stripped of its gas and dust leaving the other enriched, or the gas and dust clouds in both galaxies may be made increasingly turbulent and/or driven towards the centers of the galaxies, or sufficient energy may be transferred out to the galactic haloes for the two galaxies to merge into a single larger galaxy. Whatever the details of the interaction between the galaxies, the interstellar material within them is disturbed from its previous relatively quiescent state. Inevitably in some places that disturbance will result in an increase in density and that in turn is likely to be sufficient to trigger star formation. The more interstellar material contained within the galaxies and the more that it is concentrated into a small volume by the interaction, the stronger and more violent will be the resulting outburst of star formation. Since spiral galaxies contain the most interstellar material, interactions involving two large spiral galaxies produce the most violent starbursts and in some cases probably lead to the formation of ULIRGs.

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The timescale for collisions between galaxies is typically about an aeon. The interstellar material is thus likely to continue to be disturbed for that period of time. The starburst may therefore also persist for a similar period. It seems likely however that the lifetime of the starburst will be significantly shorter than an aeon since the interstellar material will rapidly be consumed and so little will be left to fuel starbursts during the later stages of the interaction. The lifetime of a typical starburst is thus probably limited to a few hundred million years.

Starbursts can be found within galaxies that do not appear to have been through a recent encounter with another galaxy. In these cases, the galaxies frequently possess prominent central bars. The tidal effect of the bar can draw interstellar material in towards the center of the galaxy, increasing its density and so triggering a starburst. There remain however other starburst galaxies, especially amongst the weaker starbursts occurring in small galaxies, where the cause of the starburst is still a mystery.

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