Starburst Galaxies

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Starburst Galaxies

A starburst galaxy is one undergoing a brief episode of intense STAR FORMATION, usually in its central region. The massive stars in the burst generate most of the total luminosity of the entire galaxy. Starburst galaxies are fascinating objects in their own right and are the sites where roughly 25% of all the massive stars in the local universe are being formed. They offer unique laboratories for the study of the formation and evolution of massive stars, the effects of massive stars on the interstellar medium and the physical processes that were important in building galaxies and chemically enriching the INTERGALACTIC MEDIUM.

What is a starburst?

Overview

There is no rigorous definition of a starburst galaxy, but several different criteria are often used. These are clear conceptually, but each is subject to uncertainties in its application.

Starbursts are usually located in the centers of galaxies, and have typical radii of 100–1000 pc (1–10% of the size of their 'host' galaxy). Despite their small size, they are converting gas into massive stars at a rate that exceeds that found throughout the rest of their host galaxy. The starburst is 'fueled' by a copious supply of interstellar gas (primarily in the form of molecular hydrogen) that has been accumulated in the center of the galaxy. The available gas supply is sufficient to sustain the current rate of star formation for only of order 10^8 yr ($\sim$1% of the age of the universe). The dust grains associated with the molecular gas usually absorb most of the radiation produced by the burst's stars. This can make it difficult to determine many of the basic properties of starbursts.

Star-formation rates

We do not directly measure the star-formation rate in a starburst but must infer it from measurements of the starburst's luminous output. Two techniques are routinely used.

The first is to use the bolometric luminosity of the starburst (L_{bol}), which is the luminosity integrated over the entire electromagnetic spectrum. L_{bol} for a starburst is dominated by the emission from hot, massive, short-lived stars. These have masses greater than about 8 times the mass of the Sun ($M > 8M_\odot$) with lifetimes of less than about 40 million years. The bulk of the radiation from these stars is emitted in the ultraviolet part of the spectrum. Dust grains in interstellar medium of the starburst absorb this radiation, are heated, and cool by emitting far-infrared radiation. Thus, a good approximation of L_{bol} is given by the sum of the starburst's ultraviolet and infrared luminosities.

The second technique uses measurements of the amount of ionizing radiation produced by the starburst (often denoted by Q, the total number of photons produced per second that are capable of ionizing atomic

hydrogen). The production of these ionizing photons is dominated by the most massive, shortest-lived stars ($M > 25M_\odot$ and lifetimes less than 7 million years). Measurements of Q are based on measurements of the rate at which H ions and electrons recombine, which in turn is measured by the luminosity of the so-called recombination emission lines of hydrogen (after the luminosity is corrected for absorption due to dust inside the starburst).

Given a measurement of L_{bol} or Q, we can estimate the mass of the population of massive stars required to produce this quantity. If we divide this mass by the lifetime of the appropriately massive stars we obtain an estimate of the mean formation rate of the massive stars. This technique tells us almost nothing about the rate at which low-mass stars (like our Sun) are being formed, since these stars contribute only a negligible amount to L_{bol} or Q. Indeed, it is entirely possible that starbursts form only massive stars (unlike the mode of star formation in normal galaxies like our own). If we assume that starbursts form a normal complement of low-mass stars, the implied star-formation rates usually range from $1M_\odot$ to $100M_\odot$ yr^{-1}.

The burst intensity

A useful way to define a starburst is to consider the burst intensity—the rate of star formation per unit area (Σ_{SFR}— typically given in units of $M_\odot$ per year per kiloparsec^2). In normal star-forming galaxies like our own Milky Way, the star-formation rate is a few $M_\odot$ per year throughout a galactic disk with a radius of about 10 kpc (e.g. Σ_{SFR} has a typical value of $10^{-2}M_\odot$ yr^{-1} kpc^{-2}). In a typical starburst galaxy, the star-formation rate would be $10M_\odot$ yr^{-1} in a region with a radius of 0.5 kpc. The implied Σ_{SFR} is then $10M_\odot$ yr^{-1} kpc^{-2}, or 10^3 times greater than in a normal galaxy.

It is important to emphasize that there is no particular 'magic' value for Σ_{SFR} that separates normal and starburst galaxies. A continuum of values is observed, spanning at least 6 orders of magnitude from the most quiescent star-forming normal galaxies to the most intense starbursts.

Although calculating a global value for Σ_{SFR} is a useful way to quantify a starburst, star formation is not uniformly distributed throughout the bursting region. Instead, the star formation occurs both in compact (few parsec scale) star clusters and in a more smoothly distributed mode. The most massive CLUSTERS (the 'super star clusters') have estimated masses of (10^5–10^6) $M_\odot$ and may be close analogs to young GLOBULAR CLUSTERS.

The burst duration

A starburst is by definition a transient event. The duration of a starburst (Δt) must be much smaller than the age of the galaxy in which it occurs ($\Delta t \ll 10^{10}$ yr). Another way of stating this requirement is that the present rate of star formation must greatly exceed the past rate averaged over the age of the galaxy. Unfortunately, it is difficult to accurately determine how long starbursts last.

Perhaps the most commonly used technique to estimate Δt is to calculate the gas-depletion time: the mass of interstellar gas in the starburst divided by the present rate of star formation. This is then a rough estimate of how much longer the starburst can be sustained before running out of gas. Gas-depletion times in starbursts are usually of order 10^8 yr, but they are highly uncertain for many reasons. For one thing, the mass of molecular gas is difficult to determine to better than a factor of a few since the determination relies on indirect arguments and observations of a trace molecule (usually CO). The estimated molecular gas masses range from $10^8 M_\odot$ to $10^{10} M_\odot$, increasing as a function of the luminosity of the starburst. In addition, the star-formation rate itself is quite uncertain, primarily because we do not know the rate at which low-mass stars are being formed (see above).

More sophisticated estimates of the duration of starbursts utilize measurements of Q, L_{bol} and the starburst mass plus detailed information on the stellar population (for example the relative numbers of massive main sequence and post-main-sequence stars such as red supergiants and Wolf–Rayet stars). These measurements are then compared with models for the evolution of a population of massive stars (see STELLAR EVOLUTION). Resulting estimates for burst duration range from a few million years for the smallest and least powerful starbursts (which occur in dwarf galaxies), up to 10^7 or 10^8 yr for powerful starbursts.

More generally, the minimum possible duration of a starburst is set by considerations of causality: the duration of star formation cannot be significantly less than the time for gas on one side of the starburst to 'communicate' with gas on the other side. Such 'signals' will travel at speed of sound in the gas or the velocity induced by the gravitational field in the starburst. These velocities will be of order 10^2 km s^{-1}, so $\Delta t > 10^7$ yr for a starburst with a diameter of 1 kpc. The most powerful and intense starbursts seem to turning gas into stars as fast as allowed by causality.

How do we find starburst galaxies?

The massive stars that power starbursts are mostly very hot ($T \sim 20\,000$–$50\,000$ K) and emit most of their radiation in the ultraviolet between 912 Å and roughly 2000 Å. Thus, one technique for finding starbursts is to search for galaxies that are unusually bright in the ultraviolet. The spectral region below about 3200 Å is inaccessible from the surface of the Earth, so most ultraviolet surveys for starbursts in the local universe have been conducted in the near-ultraviolet region just longward of the atmospheric cut-off. This will change in the near future as space-based ultraviolet imaging surveys are conducted at shorter wavelengths.

Starbursts are rich in interstellar gas and dust (the raw material for star formation). The primary radiative output from the massive stars (ultraviolet radiation) is absorbed by this interstellar material which then re-radiates the energy in other forms. The gas absorbs nearly all the stellar photons with energies sufficient to photoionize neutral hydrogen ($E > 13.6$ eV, or $\lambda < 912$ Å). The subsequent recombination of hydrogen or helium ions and resulting radiative cascade produce H and He recombination emission lines. The free thermal electrons in the gas can also collisionally excite ions, whose radiative decay produces emission lines. Many of the strongest lines of both types are in the visible part of the spectrum, and together constitute a few per cent of the bolometric luminosity of the starburst. Thus, another way to find starbursts is to search for galaxies with unusually bright emission lines.

The dust grains in the starburst are effective at absorbing ultraviolet photons of all wavelengths. The grains are heated by this radiation and cool by emitting radiation. The equilibrium temperatures that result from balancing heating and cooling rates are usually in the range 10–100 K, and the emitted radiation therefore lies in the mid- and far-infrared spectral region ($\lambda \sim 30$–300 μm). The survey by the INFRARED ASTRONOMY SATELLITE (IRAS) in the 1980s (which surveyed nearly the entire sky in the mid and far infrared) has produced the most extensive and best-studied sample of starbursts.

These three types of surveys select samples of starbursts that overlap one another but nevertheless have important systematic differences. The most direct difference is that dusty starbursts are preferentially detected in the far-infared surveys, while the less dusty starbursts are preferentially found by the ultraviolet and emission-line surveys. Dust grains are made of elements heavier than H or He ('metals'). Thus, the dust-content of starbursts correlates well with chemical composition: typically only a few per cent of ultraviolet radiation escapes 'metal-rich' starbursts (having chemical composition like the Sun) while the majority of the ultraviolet light escapes the most 'metal-poor' starbursts. Metal-poor starbursts tend to be less powerful and to occur in smaller and less massive galaxies (as a result in part of the well-known mass–metallicity relation for galaxies).

What causes a starburst?

From a purely empirical point of view, the causes of starbursts become increasingly clear for starbursts of greater and greater luminosity. The most luminous starbursts in the local universe are the so-called 'ultra-luminous infrared galaxies', which have bolometric luminosities of roughly $10^{12} L_\odot$ (nearly all of which is emitted in the mid- and far-infrared). The power source is deeply buried inside a dense, dusty region of molecular gas only a few hundred parsecs in size and may consist of a combination of a starburst and a dust-enshrouded QUASAR. The mass of molecular gas ($\sim 10^{10} M_\odot$) is comparable with the entire mass of the interstellar medium in a big SPIRAL GALAXY.

These ultraluminous galaxies almost invariably have highly disturbed morphologies that are strongly suggestive of the ongoing or recently completed merger of two large DISK GALAXIES. Specific morphological structures indicative of mergers include long narrow 'tidal tails'

of stars and gas (the remnants of the outer disks of the merging galaxies) and double nuclei. For less powerful starbursts the evidence suggests that more mild gravitational interactions between galaxies are an important triggering mechanism (e.g. the close passage of two galaxies, without their subsequent merger).

During the close passage of two galaxies, tidal stresses act to strongly perturb the orbits of the stars and gas in the galaxy disk. The dissipation of kinetic energy as gas collides with gas allows the gas to become sufficiently displaced from the stars that gravitational torques act between the stars and gas to transfer significant amounts of angular momentum from the gas to the stars. The gas can thereby flow into the center of the galaxy, where it can fuel a starburst. If the passage of the two galaxies is slow and interpenetrating enough, dynamical friction can transfer enough kinetic energy from the stars to the galaxy dark-matter halos to allow the two galaxies to merge into a single galaxy. Such mergers or strong interactions should take a few times the galaxy rotation period (about 10^9 yr), with the intense starburst phase being significantly shorter (see GALAXIES: INTERACTIONS AND MERGERS). These timescales are loosely consistent with independent estimates of starburst lifetimes discussed above.

However, many starbursts are not found in obviously interacting systems. In such cases, a stellar bar is often present in the inner disk of the starburst galaxy. A bar can act to rob gas of its angular momentum, and transfer gas into the center of the galaxy where it can fuel a starburst. The mechanism for triggering starbursts is most uncertain in the lowest-power starbursts, which occur in DWARF GALAXIES. In some cases it appears that the dwarf may have recently collided with an extragalactic gas cloud, but in most cases there is no clear evidence for any type of interaction or stellar bar.

Starbursts from a cosmological perspective

Starbursts in context
How important are starbursts? The far-infrared IRAS survey produced the best-studied sample and shows that starbursts provide about 10% of the bolometric luminosity of the entire local universe. Using the luminosities of the H recombination lines to estimate the star-formation rate (as described above), it appears that roughly 25% of all the massive stars in the local universe are formed in starbursts, while the rest are formed in the many-kpc-sized disks of normal galaxies like our own. While the measurements are difficult, and their interpretation is uncertain, a similar situation seems to hold out to a REDSHIFT of about 1 (over half the way back to the big bang).

At still higher redshifts, it becomes almost impossible to measure the amount of star formation in the large-scale disks of normal galaxies. The great distances and redshift-dimming of the light mean that only intense and luminous regions of star formation can be readily detected. The detected objects appear rather similar to local starbursts (see below), and by themselves can plausibly account for much of the early star formation in the universe.

Thus, starbursts are indeed highly significant components of the universe, past and present.

Starbursts as analogs to high-redshift galaxies
As described above, starbursts in the local universe are often selected by either their ultraviolet or their far-infrared continuum emission or by visible-band emission lines. At high redshifts ($z > 2$) the rest-frame ultraviolet, visible, and far-infrared emission from a star-forming galaxy will be observed in the visible near-infrared, and submillimeter spectral regions respectively (see GALAXIES AT HIGH REDSHIFT). With the Hubble Space Telescope and modern 10 m class ground-based telescopes operating in the visible and near infrared, and rapid advances in submillimeter astronomy, it is now possible to detect and study such high-redshift galaxies.

The ultraviolet-selected galaxies at high redshift strongly resemble similarly selected local starbursts: they have similar values for Σ_{SFR}, similar ultraviolet colors (suggesting a similar amount of reddening due to dust absorption), and their ultraviolet and visible spectra show that they have similar stellar populations and gas dynamics. One important difference is that the regions of star formation in the high-redshift galaxies are typically larger and more luminous than in ultraviolet-selected local starbursts. Depending on the uncertain corrections for dust extinction, the ultraviolet luminosities of the most powerful high-redshift galaxies imply star-formation rates that can reach several hundred $M_\odot$ per year over a region a few kpc in size. To date, less is known about the nature of the submillimeter-selected galaxies at high redshift. The available information suggests that these objects resemble the local ultraluminous galaxies described above.

It appears that the physical processes that we can study in considerable detail in local starbursts are directly applicable to high-redshift galaxies.

Galactic 'superwinds'
One of the most important processes that has been observed in both local starbursts and star-forming galaxies at high redshift is the bulk outflow of warm and hot gas at velocities close to or even exceeding the escape velocity from the galactic gravitational potential well (a phenomenon sometimes called a 'superwind'). Superwinds are driven by the collective effect of the kinetic energy that is deposited in the interstellar medium by stellar winds and supernova explosions. It is believed that this kinetic energy is converted (via shocks) into thermal energy inside the starburst. The resulting hot gas has a pressure much greater than its surroundings, and so it will expand most rapidly along the direction of the steepest pressure gradient in the interstellar medium (e.g. along the minor axis of the galaxy's gas disk). This leads to a poorly collimated bipolar outflow.

In local starbursts, there are a variety of probes of superwind physics. The hot outflowing gas produces thermal x-ray emission, and spectroscopy of this gas implies temperatures of 3–10 million K. This hot gas can

be traced out to radii of 10–30 kpc from the starburst (well out into the halo of the galaxy). The inferred outflow speeds for the hot gas are of order 10^3 km s^{-1}. Warm gas mixed into the outflow ($T \sim 10^4$ K) produces recombination and collisionally excited emission lines in the visible, and the measured Doppler shifts imply outflow speeds ranging from 10^2 to 10^3 km s^{-1}. Spectroscopy in the ultraviolet probes gas seen in absorption against the starburst. The measured blueshifts provide direct evidence for the outflow of warm and cool gas at velocities of 10^2–10^3 km s^{-1}. The ultraviolet signature of superwinds is by far the easiest one to observe in high-redshift galaxies, and it shows that outflows were common in the most actively star-forming galaxies in the early universe.

The data on both local and high-redshift superwinds establish that the outflowing material is enriched in the heavy elements (metals) that are the nucleosynthetic byproduct of massive stars (see NUCLEOSYNTHESIS). Where do these metals go? In CLUSTERS OF GALAXIES today, the amount of metals in the intergalactic medium exceeds that contained in all the stars in all the cluster's galaxies. Observations of the intergalactic medium at high redshift show that it contains at least trace amounts of metals. Thus, superwinds operating over the history of the universe are probably responsible for 'polluting' the intergalactic medium with metals.

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Growing Galaxies: Black Holes, Mergers, and Starbursts. Key points: Galaxy cannibalism; collisions and starbursts; mergers; Black hole/stellar mass relation; implications of these processes for the evolution of galaxies. Because galaxies are relatively large compared to their separations, there is a non-negligible probability to this day that they will collide. And, as these spectacular examples show, they still do! This process is the basic way galaxies grow. A starburst galaxy is a galaxy undergoing an exceptionally high rate of star formation, as compared to the long-term average rate of star formation in the galaxy or the star formation rate observed in most other galaxies. For example, the star formation rate of the Milky Way galaxy is approximately 3 M☉/yr; however, starburst galaxies can experience star formation rates that are more than a factor of 33 times greater. In a starburst galaxy, the rate of star formation is so large that the galaxy will... Starburst galaxies were much more frequent in the early universe than they are today and they played an important role in shaping the IGM throughout the history of the universe. Besides, they were responsible for forming most of the stars in the universe as they were the building blocks of present-day galaxies.