DISSECTING STARBURST GALAXIES WITH INFRARED OBSERVATIONS

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Abstract  The infrared regime contains a number of unique diagnostic features for probing the astrophysics of starburst galaxies. After a brief summary of the most important tracers, we focus in detail on the use of emission lines to probe the upper part of the main sequence in a young superstarcluster in the Antennae, and the compact, dusty starburst in the nucleus of the nearby ultraluminous infrared galaxy Arp 220.

1. Introduction

   Since stars form in the cores of dusty molecular clouds, it is not surprising that optical obscuration forms a major stumbling block for studying starburst galaxies. Since dust content and extinction correlate with stellar luminosity (e.g., Kennicutt, these proceedings), this is in particular true for the more luminous starbursts. Thus, while optical and ultraviolet (UV) observations of relatively unobscured regions in low to moderate luminosity starburst galaxies still provide excellent astrophysical diagnostics (e.g., Leitherer, these proceedings), more luminous systems require observations at near-infrared and longer wavelengths.

   However, reduced extinction ($A_K \sim 0.11A_V$) is not the only reason for observing starburst galaxies in the infrared. The infrared regime also contains an extensive set of diagnostic features which are ideal probes of the parameters of the stellar population as well as its feedback on the ambient gas:

   1. the Lyman continuum flux can be probed using hydrogen recombination lines, principally from the Paschen and Brackett series (as well as by thermal radio continuum emission);
the temperature of the ionizing radiation field can be probed using suitable ratios of helium and hydrogen recombination lines, as well as by ratios of suitable combinations of fine-structure lines (e.g., Shields, 1993; Lumsden et al., 2003; Rigby and Rieke, 2004);

a measure of the supernova rate can be obtained from the near-infrared (near-IR) [Fe II] lines, as well as from non-thermal radio continuum emission (e.g., van der Werf et al., 1993; Alonso-Herrero et al., 2003);

the age of the stellar population can be derived from any ratio of tracers that probe different temporal phases of the starburst, such as the Brγ equivalent width, effectively probing the relative importance of O-stars and red supergiants (e.g., Leitherer et al., 1999);

warm molecular gas, heated by shocks or by UV radiation, can be probed by the H2 near-IR rovibrational lines and the mid-infrared (mid-IR) rotational lines, as well as low-excitation fine-structure lines such as the [C II] 158 µm line;

extinction can be derived from ratios of hydrogen recombination lines, from ratios of H2 or [Fe II] lines arising from the same upper level, and from analysis of ice and silicate absorption features;

a possible hidden active galactic nucleus (AGN) can be revealed by high-excitation lines such as [Si vi] 1.96 µm;

emission and absorption line kinematics can be used to derive dynamical masses, and to probe bulk flows;

finally, in luminous and ultraluminous infrared galaxies, the best measure of the total luminosity of the starburst is provided by the integrated far-infrared (far-IR) emission, which typically dominates the bolometric energy output.

However, care should be taken not to apply these diagnostics blindly, since none of them is entirely straightforward, and some are only usable in limited regions of parameter space. A complete discussion of the caveats is beyond the scope of this paper, and the reader is referred to the references above for more details.

A detailed analysis, using a combination of these parameters, has been done for the nearby starburst galaxy M82 ( Förster Schreiber et al., 2001, Förster Schreiber et al., 2003), resulting in a detailed view of the spatial and temporal evolution of this starburst. More limited studies using mostly near-IR data, have been published of other nearby starbursts such as NGC 253 (Forbes et al., 1993, Engelbracht et al., 1998), NGC 1808 (Kotilainen et al., 1996), NGC 7552 (Schinnerer et al., 1997) and IC 342 (Böker et al., 1997).
In this paper we focus in particular on the use of near-IR hydrogen recombination lines to derive the Lyman continuum flux of obscured starbursts. We first discuss the spectral properties of a powerful young superstar cluster in the Antennae (NGC 4038/4039) and then contrast these to the spectral properties of the nearby ultraluminous infrared galaxy (ULIG) Arp 220. The analysis is based on near-IR H- and K-band spectra obtained with ISAAC at the ESO Very Large Telescope.

2. Near-IR spectra of a superstarcluster in the Antennae

In Fig. 1 we present near-IR H- and K-band spectra of a young, obscured superstar cluster in the Antennae. This cluster (object number 80 in the notation of Whitmore and Schweizer, 1995) is a prominent mid-IR source, producing about 15% of the total 15 μm flux density of the entire system (Mirabel et al., 1998). The spectra show the typical features expected for obscured starforming regions: the H-band is dominated by the Brackett series, with in addition a bright [Fe ii] line at 1.64 μm, and a prominent He i line at 1.70 μm. The K-band is dominated by very strong Brγ and He i 2.06 μm emission (with weaker He i emission at 2.11 μm), and a number of H2 rovibrational lines. CO absorption bands are visible at 2.32 and 2.36 μm, but are extremely faint, as expected for this very young cluster (∼ 4 Myr, Gilbert et al., 2000).

The large number of hydrogen recombination lines detected allow an accurate extinction determination. Fitting all lines simultaneously, we obtain an extinction $A_K = 0.5$, located in a foreground screen. This geometry provides a significantly better fit than a model where emitting and absorbing material are cospatial. After correction for extinction, the derived Lyman continuum flux (under the usual assumptions of case B recombination in ionization bounded, dust-free H ii regions) is $Q_0 = 1.5 \cdot 10^{53} \text{ s}^{-1}$, which implies the presence of about 35000 O-stars within a volume with a half-light radius of only 32 pc.
The effective temperature of the radiation field derived from the ratio of helium and hydrogen recombination lines is $T_{\text{eff}} \sim 38500$ K, which corresponds to the most massive stars having a Zero-Age Main Sequence spectral type of approximately O7.5. Given the derived cluster age, stars with spectral types up to O4.5 could have been present, but in that case $T_{\text{eff}} \sim 47000$ K would be expected. This value is closer to the $T_{\text{eff}} \sim 44000$ K estimated from ratios of mid-IR fine-structure lines (Kunze et al., 1996). The disagreement with the value derived from recombination lines is harmless, since the recombination line ratios are insensitive to $T_{\text{eff}}$ values above about 40000 K. More detailed analysis is required to see if this procedure can be used to establish the presence of an upper mass cutoff on the initial mass function.

Figure 2. H-band (left) and K-band (right) spectra of the nuclear starburst in Arp 220. Shaded bands indicate spectral regions affected by skylines.

3. The compact, dusty starburst in Arp 220

In Fig. 2 we present near-IR H- and K-band spectra of the compact, dusty starburst in the nucleus of the ULIG Arp 220. These spectra provide a remarkable contrast with those shown in Fig. 1. In the H-band, the only significant emission line is that of [Fe ii] which probes the supernova remnants created in the starburst. However, the Brackett series is totally absent, except for the Brγ line in K-band, which is however dominated by H2 rovibrational lines. Strong photospheric continuum from red supergiants is evident in both H- and K-band. The apparent deficiency in young, hot stars suggested by the faintness of the recombination lines has led to speculations on a hidden AGN in Arp 220 which would provide most of the bolometric luminosity (Armus et al., 1995). Alternatively, extreme foreground obscuration has been invoked to suppress the recombination lines (Sturm et al., 1996). While extinction certainly plays a role, the prominence of red supergiant features and of the [Fe ii] lines, as well as several other arguments (van der Werf, 2001) argue against extreme foreground obscuration.
The most satisfying explanation for the faintness of the recombination lines is Lyman continuum absorption by dust within the ionized regions (see also Dopita, these proceedings). If most of the ionizing radiation is absorbed by dust grains rather than hydrogen atoms, a dust-bounded (rather than hydrogen-bounded) nebula results, and all tracers of ionized gas (recombination lines, fine-structure lines, free-free emission) will be suppressed. If the H\textsc{ii} regions in Arp\,220 are principally dust-bounded, the observational properties of Arp\,220 can be accounted for, even with only moderate extinction. Since the dust also absorbs far-ultraviolet radiation longwards of the Lyman limit, the formation of photon-dominated regions is also suppressed, and the thus the same mechanism can account for the faintness of the 158 \,\mu m \,[\text{C}\,\text{ii}] line in Arp\,220 and other ULIGs (Fischer et al., 1999).

Is the Arp\,220 starburst dominated by dust-bounded H\textsc{ii} regions? The average molecular gas density in the $\sim 10^{10}$ M$_\odot$ nuclear molecular complex in Arp\,220 is $n_{\text{H}_2} \sim 2 \cdot 10^4$ cm$^{-3}$ (Scoville et al., 1997). The strong emission from high dipole moment molecules such as CS, HCO$^+$ and HCN argues for even higher densities: $\sim 10^{10}$ M$_\odot$ of molecular gas (i.e., all of the gas in the nuclear complex) has a density $n_{\text{H}_2} \sim 10^5$ cm$^{-3}$ (Solomon et al., 1990). At such densities the ionized nebulae created by hot stars are compact or ultracompact H\textsc{ii} regions, where 50 to 99\% of the Lyman continuum is absorbed by dust (Wood and Churchwell, 1989). Observationally, hydrogen-bounded and dust-bounded H\textsc{ii} regions can be distinguished by the quantity $R = L_{\text{FIR}}/L_{\text{Br}\,\gamma}$: for a wide range of parameters, $R < 3570$ implies that the nebula is hydrogen-bounded, while $R > 35700$ implies that the nebula is dust-bounded (Bottorff et al., 1998). For Arp\,220, the Br$\gamma$ luminosity of $1.3 \cdot 10^6$ L$_\odot$ (van der Werf, 2001), implies $R = 1.6 \cdot 10^5$ assuming an obscuring foreground screen with $A_V = 20^m$ (a model consistent with all infrared data). The star formation takes place in (ultra)compact H\textsc{ii} regions, where all of the usual tracers of ionized gas (recombination lines, fine-structure lines, free-free emission) are quenched, not extincted. While this result significantly complicates the interpretation of diagnostics of massive star formation in ULIGs, it is save to conclude that the properties of Arp\,220 can be accounted for by an intense, and significantly (but not extremely) obscured starburst. There is no reason to invoke the presence of extreme extinction, a strongly aged starburst, or an additional power source in Arp\,220.

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