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Viewing the Evolution of Massive Star Formation through FIR/Sub-mm/mm Eyes

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Abstract. In this paper, we present an overview of our method of constructing a family of models for the far-infrared, sub-millimeter, and millimeter (FIR/sub-mm/mm) line emission of molecular and atomic gas surrounding massive star formation in starburst galaxies. We show the results of a case study, an expanding supershell centered around a massive star cluster with a particular set of input parameters and its application to nearby starburst galaxy M 82. This set of models can be used not only to interpret the observations of FIR/sub-mm/mm line emission from molecular and atomic gas, but also to investigate the physical environment and the initial cloud conditions in massive star forming regions as well as the ages of the starbursts through simulations for a wide range of input parameters. Finally, we discuss limitations of our models, and outline future work.

1. Overview

A starburst phenomenon occurs when the star formation rate (SFR) is so rapid that it cannot be sustained for the lifetime of the galaxy. Giant molecular clouds (GMCs), especially the dense cores, are the places of active, massive star formation in galaxies. Starburst galaxies have impressive reservoirs of molecular gas at their centers to fuel the massive star formation. The effect of a newly born super star cluster (SSC) inside a GMC is to produce a hot bubble and a thin dense shell of neutral gas and dust swept up by the H II expansion, strong stellar winds, and repeated supernova (SN) explosions. Lying at the inner edges of the shells are the photodissociation regions (PDRs), the origin of much of the FIR/sub-mm/mm radiation from the interstellar medium (ISM) in starburst galaxies (see Figure 1). The bursts of massive star formation have a profound impact on the structure and evolution of their host galaxies by injecting large amounts of energy and mass into the ISM.

In the past, considerable efforts have been made on the observations of the FIR/sub-mm/mm line emission of the neutral gas in massive star forming regions of nearby starburst galaxies. Several models have been developed to interpret the observed data (e.g. Mao et al. 2000; Wild et al. 1992). They
have shown that the physical conditions (i.e. gas temperature, density, and FUV flux) are enhanced in starburst regions. The main drawback is that the extragalactic sources are far away, and hence higher resolution and sensitivity are required to map individual starburst regions in these galaxies. Theoretical starburst models can however synthesize the observations at any resolution and provide predictions and constraints for the expected gas behavior and conditions within star forming regions of galaxies.

A successful model for the FIR/sub-mm/mm line emission of a starburst galaxy must bring together in one package a wide range of physics including the dynamics of the bubble/shell structure around a young star cluster, the evolution of the stellar population, the fully time-dependent PDR chemistry, and finally, the method for solving the non-LTE line radiative transfer in molecular and atomic gas in star-forming regions. Few models, if any, have all these physical elements included at the same time. We introduce a new family of models that predict the properties of FIR/sub-mm/mm line emission from the evolving regions of massive star formation in a starburst galaxy, with particular emphasis on the neutral ISM (Yao et al., in preparation). The models follow the evolution of an ensemble of optically thick GMCs centrally illuminated by young evolving super star clusters (SSCs). A time-dependent treatment of the PDR chemistry is taken into account in the line radiative transfer modeling (Yao et al. 2006, and references therein).

In this study, we will not address issues related to the triggering mechanisms of massive star formation, which are important in understanding how starburst galaxies form and evolve. However, by comparing our predicted line intensity ratios from ensembles of expanding shells with observational data of starburst galaxies, we hope to achieve a better understanding of (1) the current physical state of molecular and atomic gas surrounding massive star formation in starburst environments; (2) the initial conditions of the GMCs prior to star formation; (3) how the changes in star-formation related parameters (metallicity, radiation field strength, ambient pressure, and star-formation rate/efficiency) affect the properties and evolution of the neutral ISM in starburst galaxies; (4) how the CO-to-H$_2$ conversion factor $X$, a parameter that is used to determine the total molecular gas mass, changes as a starburst system evolves; and (5) the relationship between a sequence of starbursts in a galaxy and the observed FIR/sub-mm/mm properties of the molecular and atomic gas to its age.

2. Application to Nearby Starburst Galaxy M 82

The starburst activity in M 82 (distance $\sim$ 3.25 Mpc) was likely triggered by tidal interaction with its companion M 81 beginning about $10^8$ yr ago in the nucleus, and is currently propagating outward. The infrared luminosity of M 82 is about $4 \times 10^{10} \, L_\odot$ arising mostly from the central 400 pc region, which has a stellar bar structure and currently has a high supernova rate of $\sim 0.05 - 0.1 \, \text{yr}^{-1}$. The evolutionary scheme in M 82 remains under debate. The most commonly suggested ages of the starburst in the central region are 3 - 7 and 10 - 30 Myr (e.g. Förster-Schreiber et al. 2003).

Using the expanding shell model described in the overview, our predictions of the CO, HCN, and HCO$^+$ line intensity ratios agree with the molecular data for the central lobes (300 - 600 pc) for a shell with an age in the 3 - 7 Myr range
Figure 1. Left: The schematic structure of an evolving GMC centrally illuminated by a compact young star cluster. Right: The ratio-ratio diagrams of the CO, HCN and HCO$^+$ line intensities.

(see Figure 1). This implies that the molecular torus is possibly a consequence of swept-up or compressed gas caused by massive star formation originating in the nucleus of M 82 such as those proposed by Carlstrom & Kronberg (1991). However, it is important to realize the foregoing interpretation of the lobes as a ring or torus is not unique. A number of authors have argued that the molecular rings may be a product of Linblad resonance instabilities associated with the gravitational effects of the bar (e.g. Shen & Lo 1996; Wills et al. 2000).

Our preliminary study also shows that the kinematic properties of the swept-up shell predicted by our model are in very good agreement with the measurements of the supershell centered around the bright SNR 41.9+58 in M 82 (e.g. Weiss et al. 1999). This implies that the expanding supershell is created by strong stellar winds and supernova explosions from a young massive star cluster ($\sim 2.5 \times 10^6 M_\odot$) located at its center (see Table 1).

| Parameter                   | Observation | Model  |
|-----------------------------|-------------|--------|
| Radius (pc)                 | 65.0        | 65.0   |
| Age (Myr)                   | 1.0         | 1.0    |
| Expansion velocity (km s$^{-1}$) | 45          | 45     |
| Total H$_2$ molecular gas mass ($\times 10^6 M_\odot$) | 8.0         | 7.6    |
| Kinetic Energy ($\times 10^{53}$ ergs) | 1.6         | 1.5    |
| Total stellar mass in the center cluster ($\times 10^6 M_\odot$) | ...         | 2.5    |
| Total number of O stars ($\geq 40 M_\odot$) | ...         | 1700   |
| Total Mechanical Energy ($\times 10^{54}$ ergs) | ...         | 1.7    |

We also modeled the $^{12}$CO line intensity ratios of high-$J$ transitions to the 1-0 transition, and the [C I], [C II] line intensity ratios for the expanding supershell centered around SNR 41.9+58 in M 82 (Figure 2). The predictions can be used for comparison with future observations, and also to constrain the
physical conditions of the gas in the shell. The model line ratios which are greater than unity at \( t < 8 \) Myr imply that CO is optically thin in the expanding supershell. Therefore, it is better to look at the high CO transitions \( (J > 3) \) in this supershell. Observational data for this region are not available in multiple lines because of the high resolution needed. However, Seaquist et al. (2006) shows some evidence for enhancement in \( r_{61} \) in the supershell at 7″ resolution. The ratio is not as high as the model prediction. However, the data do not completely isolate the supershell emission.

3. Conclusion and Future Work

Our models yield FIR/sub-mm/mm molecular and atomic line intensities and radii for shells based on initial cloud conditions appropriate for those in M 82. The models suggest that the neutral ISM of the central star-forming region is a product of fragments of the evolving shells. The good agreement between our model and observed molecular line intensities as well as the observed sizes and motions of some shell structures indicates that the set of models we have developed can be used to interpret star forming activity in other starburst systems too.

The limitations of our models are that we do not include the effects of magnetic fields, the interactions between shells or between shell and cloud, the effects of clumpy clouds and the non-uniform ambient ISM, and the effects of non-spherical cloud geometries and cloud spatial distributions.

A number of issues arise from our preliminary study of the expanding supershell in M 82. It is not clear whether our results support a physical association between the supershell and the bright SNR 41.9+58 near its center. If the SNR were within or near the SSC, there is an issue whether there is sufficient gas remaining to form an SNR after the action of the previous winds and SNe. (2). The SSC responsible for the formation of the supershell might also have provided the stellar mass for the several hundred solar mass black hole detected by Chandra X-ray observations near its center. Theories for the formation of this black hole include the collapse of a “hyperstar” formed by the coalescence of many normal stars, or the direct merger of stellar mass black holes. The SSC is adequately endowed with sufficient mass since there would have been 1,700 O stars, each with mass greater than or equal to about 40 \( M_\odot \). (3). The picture we developed for the M 82 molecular ring is similar to that of Carlstrom & Kronberg (1991), in which the primary ring or torus surrounding the nucleus is the product of star formation in the nuclear region. Though such a model yields the observed line ratios for molecular transitions, the atomic line ratios calculated by our model do not fit the observed data as well, and suggest a much older shell. This is possibly because the atomic line data have such low resolution that they correspond to a much larger region \( (> 1 \) kpc). A variety of modeling parameters and comparisons with high resolution observational data need to be considered to yield a more accurate picture and more precise ages of the starbursts in M 82.

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