Submillimeter View of Gas and Dust in the Forming Super Star Cluster in NGC 5253

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Abstract. A giant molecular cloud has been detected surrounding the supernebula in NGC 5253, revealing details of the formation and feedback process in a very massive star cluster. "Cloud D" was recently mapped in CO J = 3–2 with the Submillimeter Array. The cloud surrounds a currently forming massive cluster of mass $\sim 10^6$ M$_\odot$, and luminosity $\sim 10^9$ L$_\odot$. Cloud D is hot, clearly associated with the cluster, yet kinematically relatively quiescent. The dust mass is $\sim$15,000 M$_\odot$, for a gas-to-dust ratio of $\sim$50, nearly an order of magnitude lower than expected for this low metallicity galaxy. We posit that enrichment by the cluster, leading to a stalled cluster wind, has created the unusual conditions in Cloud D. The absence of current mechanical impact of the young cluster on the cloud, in spite of the presence of thousands of O stars, may permit future generations of stars to form near the massive cluster.

Keywords. galaxies: individual (NGC 5253), galaxies: star clusters, galaxies: starburst, galaxies: dwarf

1. Introduction

The process by which the most massive star clusters form is not well understood. The closest massive clusters, such as those in the Galactic Center or R136 in the Large Magellanic Cloud, are relatively evolved and far from their initial molecular conditions. Clusters that are still embedded in their natal clouds can provide more direct information on the interaction of young clusters with their natal clouds, including star formation efficiency and the precise nature of cluster feedback on the clouds. The advantage of submillimeter observations in the study of young clusters is that one can simultaneously trace spectral lines of molecular gas as well as continuum emission from ionized gas and dust, to give a full picture of the gas, dust, and kinematics in young, forming clusters.

The massive cluster in NGC 5253 may be the closest example of a embedded cluster still in the process of formation. Despite having little gas and no disk, this dwarf spheroidal galaxy has formed hundreds of clusters in the recent past (Calzetti *et al.* 1997, 2015, Chandar *et al.* 2005, Harbeck *et al.* 2012, de Grijs *et al.* 2013). This unlikely environment is the location of the "supernebula", a bright and compact radio continuum source associated with a luminous HII region (Beck *et al.* 1996, Turner *et al.* 2000). The HII region core is $\sim$1 pc in radius with an infrared luminosity of $\sim 10^9$ L$_\odot$ at D = 3.8 Mpc, and Lyman continuum rate of $\sim 7 \times 10^{52}$ s^{-1} (7000 O7 star equivalents) (Meier *et al.* 2002). The supernebula is embedded, with A$_v$ $\sim$ 16 (Turner *et al.* 2003, Alonso-Herrero *et al.* 2004). Most of the gas in NGC 5253 resides *outside* the galaxy, in a halo of HI filaments (Kobulnicky & Skillman 2008; López-Sánchez *et al.* 2012) and in a molecular streamer of $\sim$200 pc extent detected in CO (Turner *et al.* 1997). The streamer is infalling along the minor axis of the galaxy. No CO(1–0) and only weak CO(2–1) had been detected until

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recently at the location of the embedded SSC/supernebula (Turner *et al.* 1997; Meier *et al.* 2002; Miura *et al.* 2015).

Submillimeter Array observations of the J = 3–2 transition of CO and dust continuum in NGC 5253 have revealed the giant molecular cloud (GMC) associated with the supernebula and its embedded cluster. "Cloud D" is shown in Figure 1 (Turner *et al.* 2015). Cloud D is unusually bright in CO(3–2), 2.6 times brighter than in CO(2–1). The emission is optically thin and the inferred gas temperature is >200 K, with densities of $\sim 5 \times 10^4$ cm^{-3}. Galactic GMCs, even those actively forming stars, more typically have temperatures of $\sim$10-15 K on these scales. From its temperature alone, it is clear that Cloud D is closely associated with the young massive cluster.

To determine a star formation efficiency for the cluster we need a gas mass, which is difficult to determine for this strange cloud. From the CO(3–2)/CO(1–0) ratio it is inferred that the emission is optically thin; by contrast, Galactic GMCs are optically thick in CO. Thus we cannot use the standard Galactic conversion factor, X_{CO}, which applies to optically thick and cooler Galactic clouds in the CO(1–0) transition. Cloud D is as yet undetected in CO(1–0). For optically thin emission, instead one counts emitted photons in the line and from that computes the total number of CO molecules from the partition function. However, to get to the total molecular mass requires a relative abundance of CO to H$_2$, and this abundance depends on the chemistry. The chemistry is uncertain in Cloud D because of the unusually high temperature of the cloud, the high radiation fields, and the low metallicity of NGC 5253, $Z \sim 0.25 Z_\odot$ (Kobulnicky *et al.* 1997, López-Sánchez *et al.* 2007). Using the Galactic value of [CO]/[H$_2$] = 8.5×10^{-5} we infer a total H$_2$ mass of $M_{H_2} = 5 \times 10^4$ M$_\odot$ (Turner *et al.* 2015); however, given the unusual properties of this cloud we have no confidence that the Galactic CO abundance ratio obtains here.

A less slippery number for the gas mass can be determined from subtracting the stellar mass from the dynamical mass of the cloud. The uncertainties are simpler and better constrained than the previous methods; it gives a total gas mass rather than an H$_2$ mass, which is more appropriate for star formation efficiency. The mass of stars can be obtained from the Lyman continuum rate (Meier *et al.* 2002) and the 3.5 Myr age based on Br γ equivalent widths (Alonso-Herrero *et al.* 2004) and Wolf-Rayet signatures in abundances (Walsh & Roy 1989, Kobulnicky *et al.* 1997, López-Sánchez *et al.* 2007). Calzetti *et al.* (2015) argue that dust emission affects the Br γ EW and that the age of this cluster is closer to 1 Myr, and further divide the stars among two clusters, both within Cloud D. However, this young age would not explain the Wolf-Rayet signatures and local nitrogen enhancement in the region, so we favor an older age. For a 3.5 Myr age, and assuming continuous star formation, the stellar mass based on STARBURST99 models is $M_{stars} = 1.1^{+0.7}_{-0.2} \times 10^6$ M$_\odot$. The CO linewidth is $\sigma = 9.2 \pm 0.6$ km s^{-1}; this will give an upper limit to the gravitational mass, which is $M_{vir} = 1.8^{+0.2}_{-0.7} \times 10^6$ M$_\odot$. The final gas mass is then $M_{vir} - M_{stars} = 7 \pm 4 \times 10^5$ M$_\odot$, giving a star formation efficiency $M_{stars}/(M_{stars} + M_{gas}) \sim 60\%$ (Turner *et al.* 2015). This very high, record efficiency, not so different from the 75±50% inferred from CO(2–1) using X_{CO} by Meier *et al.* (2002), bodes well for the cluster's survival.

2. Cloud D: A Very Dusty Cloud

An alternative path to the gas mass is through dust, but the dust mass of Cloud D is also strange and interesting. About half of the 72 mJy of 870μm continuum emission, 34±14 mJy, is from dust; the rest is free-free emission from the ionized gas. Using the dust opacity of the Large Magellanic Cloud (Galliano *et al.* 2011), and a dust temperature of
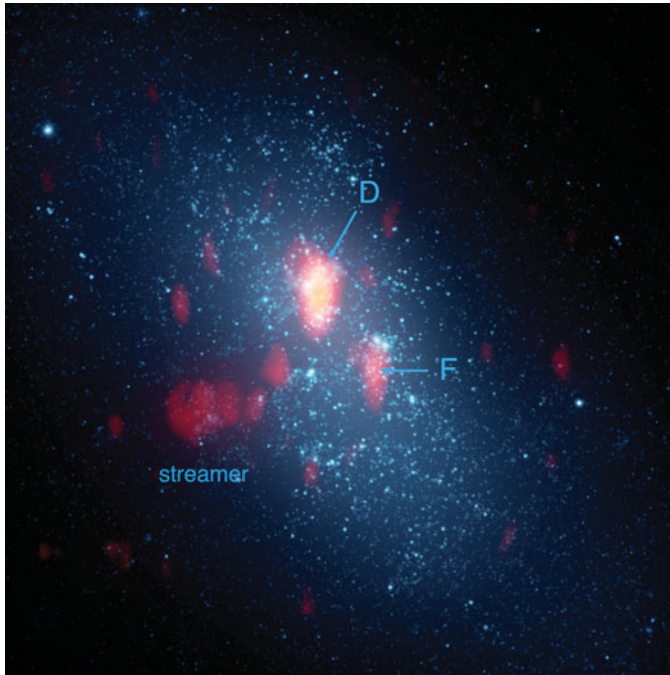
Figure 1. Molecular gas in NGC 5253. CO(3-2) emission overlaid on an HST image. The CO image is from the SMA, beam is $4''$ x $2''$. "Cloud D" is the brightest CO source near the center; also detected are another cloud, "F" and the "streamer", which is the extended filament to the east. Turner *et al.* 2015.

46 K (Thronson & Telesco 1986) we obtain $M_{dust} = 1.5 \pm 0.2 \times 10^4$ M$_\odot$. If we scale the gas-to-dust ratio, GTD, of NGC 5253 to match its $Z \sim 0.25 Z_\odot$ metallicity, a common and reasonable assumption, we would estimate that $GTD \sim 500-700$, similar to values in the Magellanic Clouds, and this would give a dust-predicted gas mass of $M_{gas} \sim 10^7$ M$_\odot$. This is more than five times higher than the gas mass could possibly be, based on the dynamical mass of Cloud D. From the inferred gas mass we infer that instead $GTD \sim 50$ in NGC 5253, a factor of three less than the Galactic GTD value (Turner *et al.* 2015).

The reason that NGC 5253 has ten times more dust than expected may be enrichment by the cluster stars, metals that are as yet trapped within the natal cloud. STARBURST99 models for clusters of this luminosity that are more than 3 Myr of age can produce 30,000 M$_\odot$ of metals, twice the dust mass that is seen. So it is not surprising, it is even expected, that enrichment is taking place.

The dust enrichment has potential implications for the evolution of the cluster and its cloud, and the nature of feedback. Cloud D is surprisingly quiescent; its linewidth of ~ 9 km s^{-1} is not far from the value expected for a cloud of its 25 pc size based on the Galactic size-linewidth relation. Yet its high temperature and precise positional and kinematic coincidence with the massive cluster indicates a close association of the two. Where is the feedback from the 7000 O stars?

Silich *et al.* (2004) and Tenorio-Tagle *et al.* (2007) suggest that enrichment by cluster stars creates a dusty environment that can enhance gas cooling and stall a cluster wind. Based on numerical modeling of the gas dynamics they find that for a cluster of the luminosity exciting the supernebula in NGC 5253, an enrichment of $1.5 Z_\odot$ is sufficient to stall a wind, trapping the enriched products of stellar evolution within the cloud. From the mass of dust it would appear that the enrichment of the gas in Cloud D is roughly

twice this amount. The stalled wind model could explain both the quiescence of Cloud D and its dustiness. Given the relative quiescence of this cloud, so similar to Galactic GMCs, it would seem that conditions are ripe for the formation of even more stars at this location, given an influx of gas. This is a very interesting suggestion (Silich *et al.* 2004; Tenorio-Tagle *et al.* 2007) in light of the fact that multiple generations are observed to be present in globular clusters (see also R. Wünsch this volume).

3. Conclusions

Submillimeter Array maps of CO(3–2) and 870μm dust continuum emission from Cloud D associated with the young, embedded massive cluster exciting the supernebula in NGC 5253 allow the determination of dynamical mass, gas mass, and dust mass for this cloud, and allow us to define the interaction of the cluster and its surroundings.

1) The molecular gas in Cloud D is hot; the CO(3–2)/CO(2–1) line ratio suggests that the temperature is unusually warm, > 200 K. The cloud is clearly heated by the cluster.

2) The H_2 mass obtained from the line intensity of the optically thin CO emission is low, particularly compared to the dust mass. This is probably due to the $[CO]/[H_2]$ abundance ratio, which is highly uncertain in this unusually warm and highly irradiated cloud. Instead we obtain a gas mass by subtracting the stellar mass, based on the Lyman continuum rate and STARBURST99 models and a 3.5 Myr age, from the dynamical mass based on the CO size and linewidth of Cloud D. The gas mass of 7×10^5 $(D/3.8\,\text{Mpc})^2$ gives a record high star formation efficiency of 60%.

3) The dust mass is high for the metallicity of the galaxy: gas-to-dust radio is 50:1, sub-solar, much lower than the 500-700 value expected based on the low metallicity of NGC 5253. We posit that the dust mass is almost entirely produced by the stars of the cluster; STARBURST99 models predict twice this yield in metals for a cluster of this luminosity and 3.5 Myr age, so this model is entirely plausible.

4) The numerical models of Silich *et al.* (2004) predict that a cluster wind will catastrophically cool and stall if the gas is enriched to 1.5 $Z_\odot$ for the supernebula cluster in NGC 5253. This condition appears to be met. This could explain why, even in the presence of 7000 O stars and a high cloud temperature, the width of the CO line, 9.2 km/s, roughly that expected for a quiescent cloud of its size based on the Galactic size-linewidth relation. Cluster feedback of the mechanical variety appears to be inhibited in this cluster, which could allow further accretion and future generations of stars to form in this cluster.

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Discussion

BOESGAARD: How did you get the metallicity?

TURNER: The overall metallicity of NGC 5253, $Z \sim 0.25 Z_{\odot}$, is from observations of the surrounding HII regions. Optical emission lines cannot be detected from the supernebula directly, which is embedded in Cloud D. The extinction is about 16 magnitudes in the visual. The gas-to-dust ratio is directly computed from the gas mass of Cloud D and observed dust mass.