Exploring the Limits of Star Formation from the Extreme Environments of Starbursts to the Milky Way

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Summary

Our goal is to combine local estimates of star formation (SF) in regions in the Milky Way with spatially resolved estimates in nearby starbursts in order to understand the physical nature of SF. More specifically, we will investigate the SF-gas surface density relations in both young stellar objects (YSOs) and massive SF clumps in the Galaxy, and in the extreme star-forming environments of interacting/starburst galaxies.

We explore the SF-gas relation in our Galaxy, normal spirals, and starburst/interacting galaxies on spatially resolved scales in three parts:

1) We measure the SF and gas surface densities in a sample of class I and flat SED young stellar objects (YSOs) from the c2d project (Evans et al. 2009) and massive, dense, clumps containing multiple SF cores from the sample of Wu et al. 2009, in prep. (see **Figures 1-3** and **Table 1**) .
2) We investigate spatially resolved SF-gas relation in the extreme environments of starburst/interacting galaxies using integral field spectroscopy with VIRUS-P (see **Figures 4 & 5**). We will compare our ongoing survey of starbursts with a complementary study of normal spiral galaxies from **VENGA (**Blanc et al., in prep), as well as other studies from the literature.
3) We will compare our findings in parts 1 & 2 to try and understand if there is a physical basis for the SF-gas scaling laws that are found in both extragalactic studies and our Galactic study (**see Figure 5**).

Our preliminary results are:

1) Follow up observations of c2d class I and flat SED YSOs were done using the Caltech Submillimeter Observatory (CSO) show that ~80% of YSOs at low extinction (A_V) are not associated with dense HCO^+(J=3-2) gas. These could be either background galaxies or older stage YSOs (**Figures 1 & 2; Table 1**).
2) Removing the YSOs with non-HCO^+ detections, we find the SFR-gas surface density relation for YSOs and massive clumps to be offset from the relations established in extragalactic studies (Kennicutt 1998, 2007; Bigiel et al. 2008; Blanc et al. 2009; Figure 3).
3) At low gas densities, YSOs are found to lie at the highest SFR surface densities of normal spiral galaxies (Figure 5).
4) YSOs in gas density peaks have slightly higher SFR surface densities than those found in starburst/interacting galaxies (Figure 5).

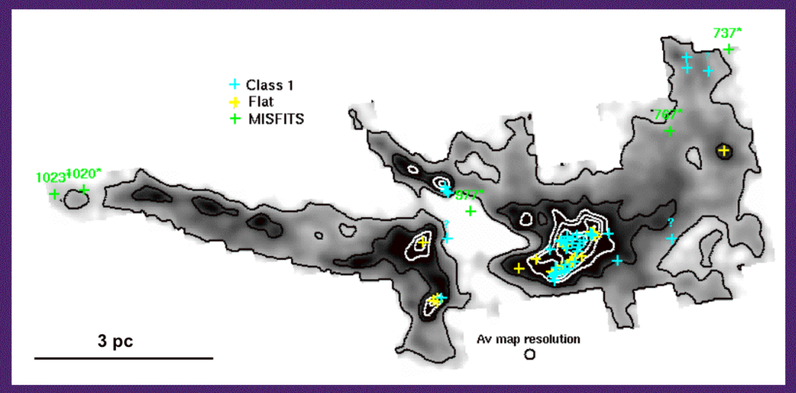

Figure 1. Extinction (A_V) map of the Ophiucus (OPH) molecular cloud. Contours show intervals in A_V where the gas surface densities were estimated. We use the number of flat SED and class I YSOs to estimate a SFR since, unlike class II/III YSOs, they are less likely to have moved far from their birth place. The crosses show the distribution of class I (cyan) and flat SED (yellow) YSOs from the *Spitzer* c2d survey. The green crosses indicate suspicious "misfit" c2d sources that lie at low extinction. Follow up observations at the CSO using the HCO^+(J=3-2) line (see **Table 2; Figure 2**) show that most of the "misfit" sources are not associated with dense molecular gas. The non-associations with dense gas signify that these sources are not younger YSOs and could be either background galaxies or older stage YSOs.

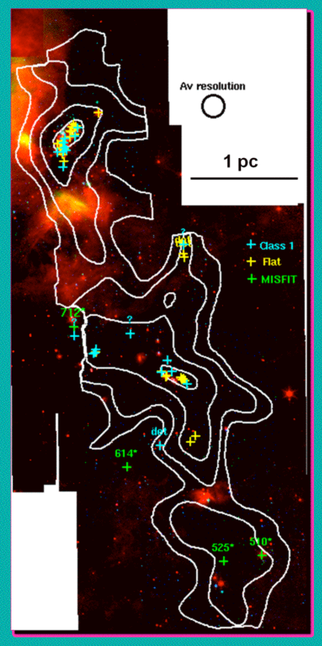

Figure 2. A three color *Spitzer* image (red= 24μm, green=8μm, blue=4.5μm) of molecular cloud Serpens is shown with A_V contours corresponding to regions where gas and SFR surface densities were measured. "misfit" or suspicious YSOs that were not found to be associated with dense HCO^+ gas and are at low A_V are marked with green crosses (see Figure 1 & Table 1).

Non-Detections in HCO+(J=3-2) from CSO						
Name	**c2d Classification**	**Spectral Index**	**Tbol'**	**Lbol'**	**SED Class**	**Envelope? Y/N**
614SERP	YSOc_star+dust(IR1)	0.68	750	0.24	flat	N
712SERP	red	1.24	130	0.14	flat	Y
525SERP	YSOc_star+dust(IR1)	0.14	770	0.48	I	N
510SERP	YSOc_star+dust(IR1)	-0.42	1200	1.1	I	N
737OPH	YSOc_star+dust(IR1)	0.99	930	0.012	flat	N
767OPH	YSOc	0.01	460	0.007	I	N
977OPH	YSOc_star+dust(MP1)	-0.78	2300	0.02	I	N
1023OPH	YSOc_red	0.37	1000	0.012	flat	N
1020OPH	YSOc_PAH-em	0.27	810	0.049	I	N
28LUP	YSOc_PAH-em	0.31	260	0.13	flat	N
34LUP	YSOc_star+dust(IR1)	0.14	3100	0.017	I	N
Detections in HCO^+(J=3-2) from CSO						
527SERP	YSOc_red	1.05	180	0.078	flat	Y
529SERP	YSOc_red	1.27	120	1.3	flat	Y
588SERP	YSOc	-0.13	740	4.7	I	Y

Table 1. Results from our follow up observations of suspicious "misfit" protostars at the CSO. About 80% (11/14) of the YSOs that lie at low A_V are not found to be associated with dense HCO^+ gas. These non-detected sources could either be background galaxies or older stage YSOs. The 3 Serpens (SERP) sources that were detected are found to also be associated wth extended emission at 1.1mm and are clustered at low A_V.

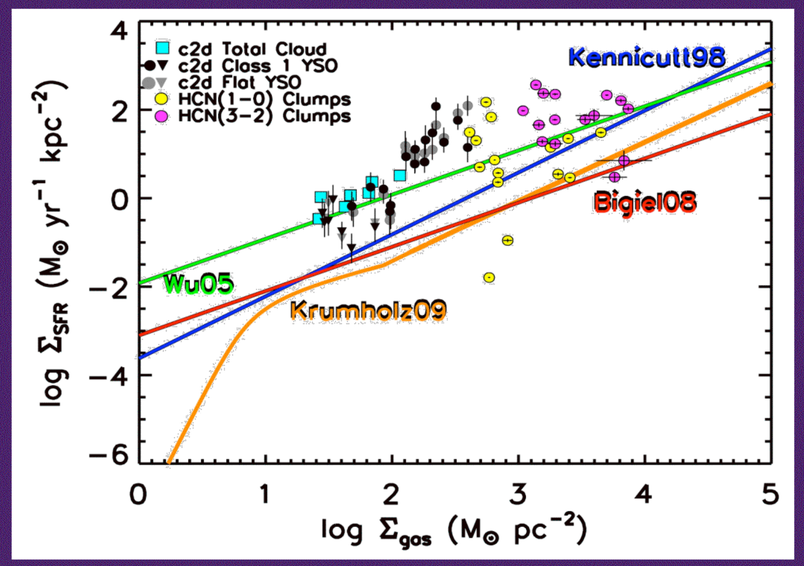

Figure 3. The SF-gas relation in YSOs from c2d survey (Evans et al. 2009) and in massive dense clumps (Wu et al., in prep). We show observational relations from global averages in spiral and starburst galaxies (Kennicutt 1998) , spatially resolved study of spirals and dwarf galaxies (Bigiel et al. 2008), and the relation found from dense gas in Galactic clumps and galaxies, as well as the theoretical prediction from Krumholz (2009). We plot only YSOs found at high extinction or that are associated with dense gas and show upper limits found at low A_V as downward triangles (Table 2, Figures 1 & 2). We find the YSOs and massive clumps have higher SFR surface densities for a given gas surface density. Both YSOs and massive clumps lie above both observational and theoretical extragalactic relations.

Virus-P Investigation of the eXtreme ENvironments of Starbursts

- We investigate the spatially resolved SF-gas relations in a sample of 20 starburst/interacting galaxies using Ha emission measured from VIRUS-P (VP) integral field unit spectrograph at McDonald Observatory as well as CO(J=1-0) an HI maps from the literature. Our sample range over a variety of interaction stages, SFRs, and gas densities (see Figures 4 & 5).
- We will explore the SF-dense gas relation in a subset of our sample galaxies using Ha line emission from VP and dense HCN(1-0) gas maps from CARMA.
- This work will not only test the assumptions of SF recipes used in simulations of galaxy interactions/mergers, but will provide a basis for future theoretical work. This in turn, will significantly impact our understanding of galaxy evolution through mergers and interactions.

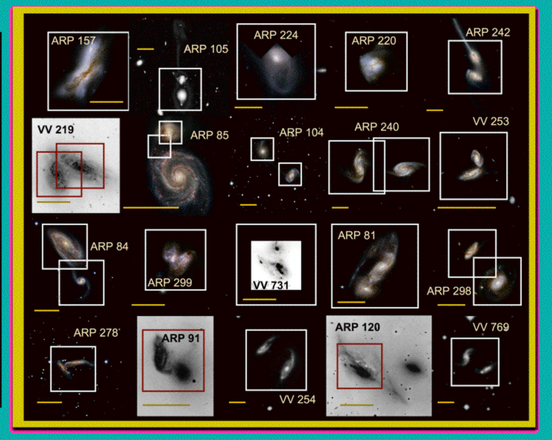

Figure 4. Optical images of our sample of 20 Starburst/interacting galaxies. The **white** and red squares indicate the 1.7'x1.7' VIRUS-P field of view and yellow bars show a scale of 10 kpc. Our sample ranges from early (close pairs) to late (merger remnant) interaction stages. The estimated gas surface densities in these systems range a factor of 1000 (see Figure 5). Our VIRUS-P survey is scheduled to be complete in early 2010.

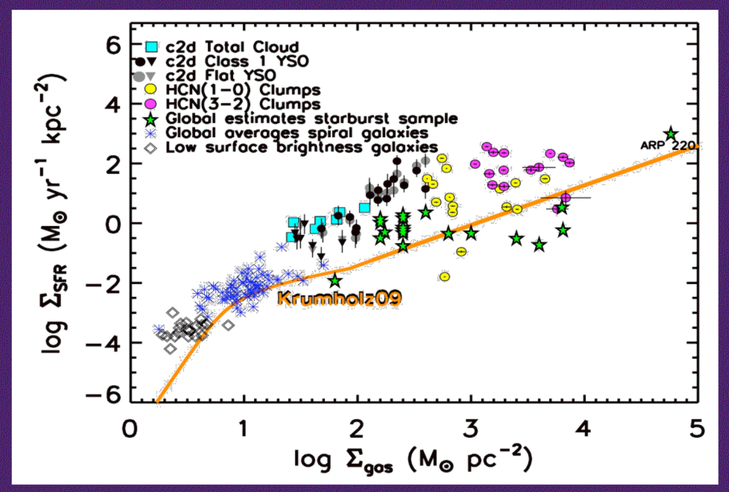

Figure 5. Estimates of the *global* averages in SFR surface densities from the far infrared or Ha images and gas surface densities from CO(J=1-0) maps are shown for our starburst sample. We compare these estimates to global averages in spiral galaxies (Kennicutt et al, 1998), low surface brightness galaxies (Wyder et al. 2009), and theoretical predictions from Krumholz et al. 2009. We also show points from our massive Galactic clumps and YSOs. Our sample of starburst/interacting galaxies range a factor of 1000 in gas densities and will allow us to test the theoretical predictions in a spatially resolved manner at high gas densities for the first time.