A Case Study of Triggered Star Formation in Cygnus X

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Overview

- Galactic and extragalactic star formation
- Physical and statistical model of star formation
- Star forming region - Cygnus X
- Cometary feature
- Distribution of molecular gas - presence of outflows
- Infrared continuum emission - dust mass
- Molecular line emission data - column density
- Possible sources of ionization

Region of Interest: Cygnus X

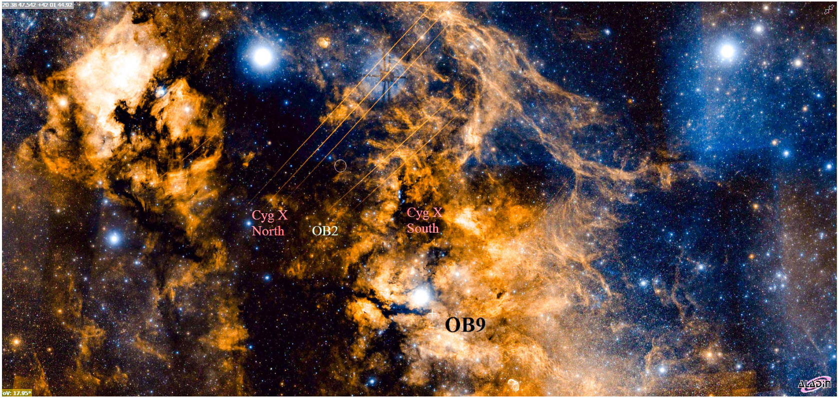


Figure: Relative locations of major segments of Cygnus region . The red circle above OB2 shows the location of the cometary feature (source: SIMBAD).

Region of Interest: Cygnus X

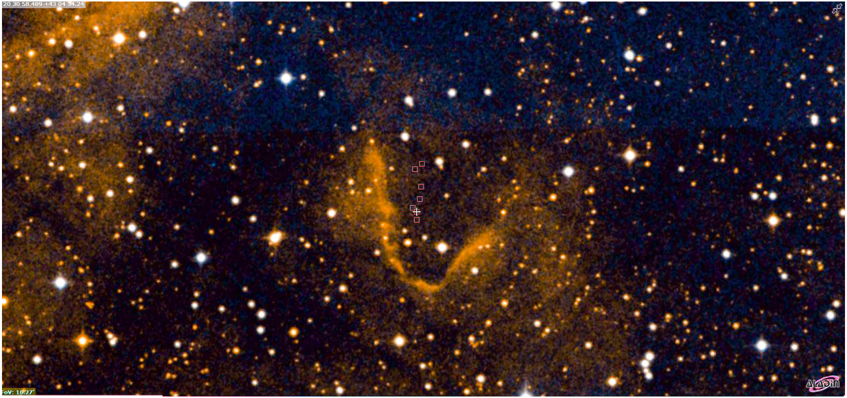


Figure: Cometary feature (source: SIMBAD)

Dust Emission Data: Structure of the Comet

- Raw data obtained at dissimilar resolution

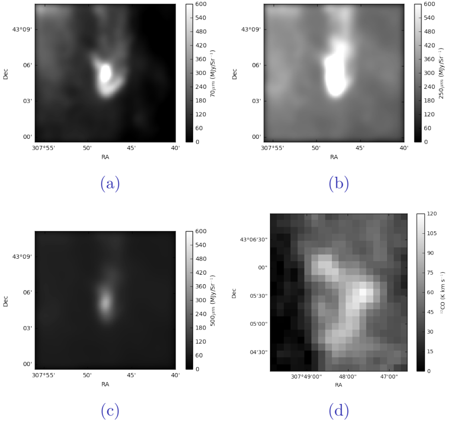


Figure: (a), (b), (c) Total intensity distribution of convolved dust emission data, along with (d) integrated intensity map from ^{12}CO line.

Spectral Energy Distribution and Mass

- Optically thick dust cloud
- From radiative transfer processes:

$$\begin{aligned} I_\nu(s_0) &\approx B_\nu(T)(1 - e^{-\tau_\nu(s_0)}) \\ &\approx \tau_\nu(s_0) B_\nu(T) \\ &\approx \left(\kappa_\nu \int_0^{s_0} \rho(s) ds \right) B_\nu(T). \end{aligned}$$

- Dust intensity model: $I_\nu = \Sigma_{dust} \kappa_\nu B_\nu(T)$, κ_ν is adopted as (Hildebrand 1983), $\kappa_\nu = 0.1 \frac{cm^2}{g} \left(\frac{\nu}{1THz} \right)^\beta$
- Fixed temperature T=15 K of dust cloud is assumed:
- Mass of the cometary structure is estimated as 400M$_\odot$

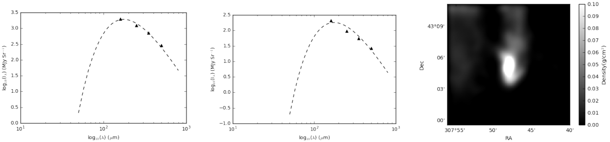
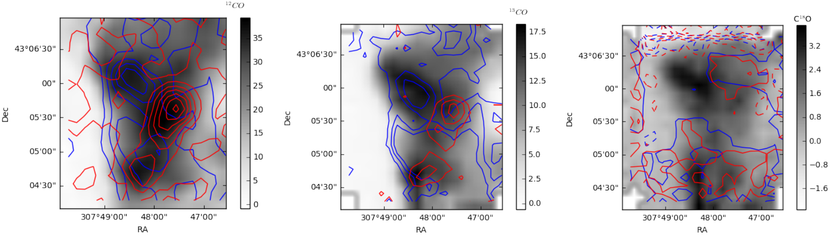


Figure: SED: fitted (dashed line) and observed (triangles) for (a) core of the comet and (b) comet head; (c) represents surface density map of H_2 with background emission removed

CO(3-2) Line Emission

- ^{12}CO ^{13}CO, C^{18}O lines reveal the presence of two molecular outflows, identified as G81.424+2.140 and G81.435+2.147 (SIMBAD):

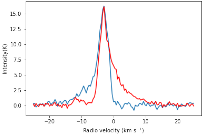


(a) (b) (c)

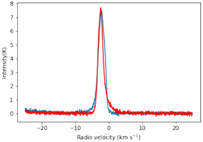
Figure: Velocity-integrated intensity plots showing the outflows in the cometary feature in (a) ^{12}CO, (b) ^{13}CO, and (a) C^{18}O lines. Red and Blue contour lines represent red and blue shifted emissions, plotted in the background of total emission shown in gray.

CO(3-2) Line Emission: Bipolarity

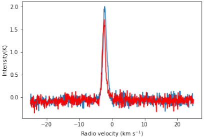
- Bipolarity in terms of deviation of intensity from Gaussian symmetry



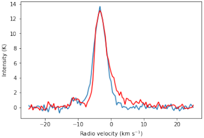
(a) G81.435+2.147



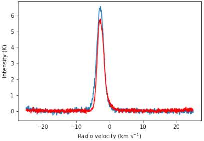
(b) G81.435+2.147



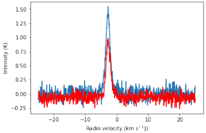
(c) G81.435+2.147



(d) G81.424+2.140



(e) G81.424+2.140



(f) G81.424+2.140

Figure: A side-by-side comparison between the outflows G81.424+2.140 and G81.435+2.147 in (a),(d) ^{12}CO, (b),(e) ^{13}CO, and (c),(f) C^{18}O lines. The asymmetry in intensity about the central velocity(frequency), which is associated with regions at rest with respect to Earth's frame, indicates the strength of bipolarity (red and blue colors denote redshift and blueshift respectively).

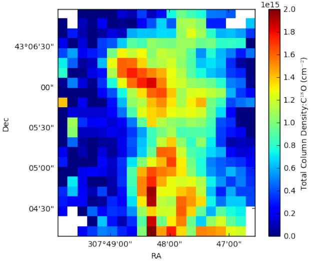
CO line Emission: Column Density

- Optically Thick ^{12}CO lines: $\tau_\nu >> 1$
- Optically thin C^{18}O lines: $\tau_\nu << 1$
- Not optically thin ^{12}CO lines: $\tau_\nu \gtrapprox 1$
- Common excitation temperature: $T_{\rm ex} = \frac{h\nu/k}{ln\left[1+\frac{h\nu/k}{T^*+J_\nu(T_{\rm bg})}\right]}$, $J_\nu(T) = \frac{h\nu/k}{e^{\frac{h\nu}{kT}}-1}$

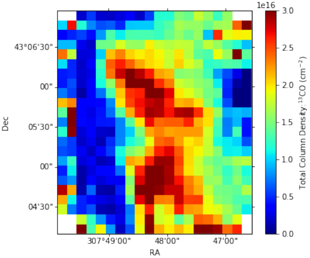
  (optically thick emission)
- Optical depth for C^{18}O: $\int \tau_\nu {\rm d}v = \frac{\int T_{\rm R} dv}{J_\nu(T_{\rm ex}-J_\nu(T_{\rm bg})}$
- Optical depth for ^{13}CO:$\tau_\nu = -ln\left[1 - \frac{T_R}{J(T_{\rm ex}-J(T_{\rm bg}}\right]$
- Molecular column density in level u for a rotational transition $u \rightarrow l$:
  $N_u = \frac{8\pi\nu_0^3}{c^3 A_{ul}} \frac{1}{e^{\frac{h\nu_0}{kT_{\rm ex}}}-1} \int \tau_\nu dv$
- Total column density: $N_{\rm tot} = \frac{Q_{\rm rot}}{g_u} exp\left(\frac{E_u}{kT_{\rm ex}}\right) N_u$,
  $Q_{\rm rot} = \sum_{J=0}^{\infty}(2J+1)exp\left(-\frac{E_J}{kT}\right)$(Mangum & Shirley 2017).

CO line Emission: Column Density

- Optically Thick ^{12}CO lines: $\tau_\nu >> 1$, optically thin C^{18}O lines: $\tau_\nu << 1$, not optically thin ^{12}CO lines: $\tau_\nu \gtrapprox 1$



(a)

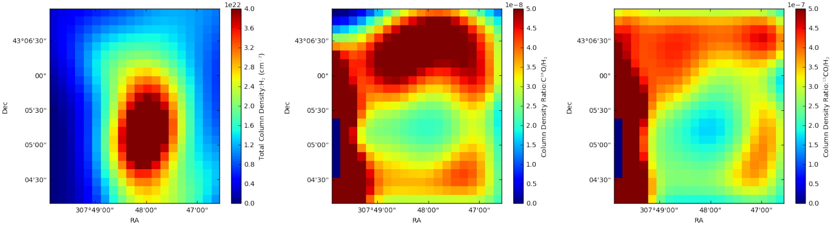


(b)

Figure: Spatial maps of total column density in the cometery region in C^{18}O and ^{13}CO lines.

CO Column Density vs H_2 Column Density

- 2.32 m_H of mass for every H_2 molecule
- Convolution of ^{13}CO and $C^{18}O$ emission



(a) (b) (c)

Figure: (a) Column density of H_2, (b) column density ratio of $C^{18}O$ to H_2, (c) column density ratio of ^{13}CO to H_2.

Source of Ionization? Ongoing Work..

- Presence of cold, dense atomic hydrogen gas cloud to the north of cometary feature
- HI self-absorption
- Thick rim in optical as well as in radio continuum
- Ionizing source: OB2 complex vs single star

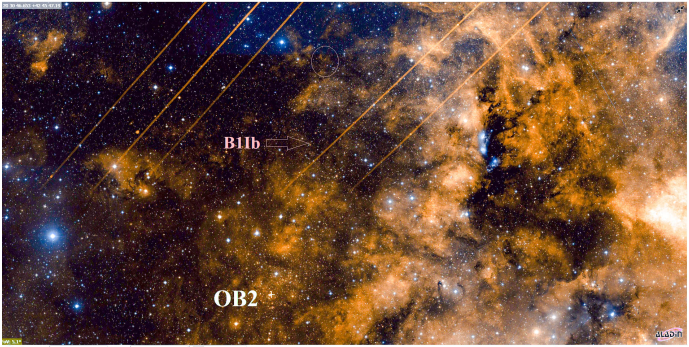


Figure: Position of single stellar object, as potential source of ionization (source: SIMBAD).

Thank You!