Searching for Converging Flows of Atomic Gas onto a Molecular Cloud

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Abstract

We present new observations of [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine structure line emission from an isolated molecular cloud using the upGREAT instrument on board SOFIA. These data are analyzed together with archival CO $J$=1–0 and H I 21 cm emission spectra to investigate the role of converging atomic gas flows in the formation of molecular clouds. Bright [C II] emission is detected throughout the mapped area that likely originates from photodissociation regions excited by UV radiation fields produced by newborn stars within the cloud. Upon spatial averaging of the [C II] spectra, we identify weak [C II] emission within velocity intervals where the H I 21 cm line is brightest; these are blueshifted relative to velocities of the CO and bright [C II] emission by 4 km s$^{-1}$. The brightness temperatures, velocity dispersions, and alignment with H I 21 cm velocities connect this [C II] emission component to the cold, neutral atomic gas of the interstellar medium, known as the cold, neutral medium (CNM). We propose that this CNM feature is an accretion flow onto the farside of the existing molecular cloud. The mass infall rate is $3.2 \times 10^{-4} M_\odot$ yr$^{-1}$. There is no direct evidence of a comparable redshifted component in the [C II] or H I 21 cm spectral lines that would indicate the presence of a converging flow.

Unified Astronomy Thesaurus concepts: Interstellar clouds (834); Molecular clouds (1072); Photodissociation regions (1223); Neutral hydrogen clouds (1099); Interstellar phases (850); Molecular gas (1073); Cold neutral medium (266)

1. Introduction

A key step in the star formation sequence is the assembly of interstellar clouds of near-fully molecular gas in which conditions are most favorable for generating new stars. This transition from atomic to molecular gas is fundamentally a microscopic, chemical process in which H$_2$ molecules form on grain surfaces while other molecular constituents develop via gas–phase or gas–grain chemistry. However, macroscopic interstellar mechanisms are also required to accumulate gas and dust into more opaque, high density, discrete configurations that allow these chemical reactions to take place and more importantly, to sustain high molecular gas fractions. Specifically, sufficient column densities of dust grains and H$_2$ are required to self-shield H$_2$ molecules (and CO, the primary gas coolant capable of reducing gas temperatures below $\approx$100 K and the spectroscopic tracer of cold H$_2$) from dissociating far-ultraviolet radiation (Hollenbach et al. 1971). Over the last 50 yr, there have been many proposed macroscopic mechanisms to form molecular clouds. These include gravitational instabilities in spiral arms and the agglomeration of existing, small molecular clouds into giant molecular clouds (McKee & Ostriker 2007; Dobbs et al. 2014). To date, there has been no observational validation of any mechanism.

A recent development based on an earlier concept of cloud assembly posits that molecular clouds emerge within the interface regions of large-scale converging streams of neutral atomic gas that develop from expanding supernova remnants, stellar winds, or spiral density waves (Ballesteros-Paredes et al. 1999; Hennebelle & Pérault 1999; Heitsch et al. 2006; Vázquez-Semadeni et al. 2009). The interaction of two converging streams produces shocks and triggers both gravitational and thermal instabilities that drive more gas from the warm, neutral medium (WNM) phase into the cold, neutral medium (CNM) phase, and ultimately, into the molecular gas phase. The resultant high gas volume density of the interface regions enables rapid formation of H$_2$ on dust grains. Once established, a molecular cloud can continue to accrete material from these extended flows, which may sustain star formation activity over several cloud freefall timescales.

While the H I 21 cm line would appear to be the obvious probe of an atomic gas flow, H I 21 cm emission does not distinguish between the more widely distributed warm neutral gas and the cold, neutral component that is the likely atomic precursor to molecular gas. In addition, the rotational motions of the galaxy, as well as noncircular motions, conspire to blend the H I emission from physically unrelated volumes of gas, making the spatial and kinematic connection of the atomic gas to the underlying molecular cloud in CO emission very uncertain.

Computational simulations of converging flows with simplified chemical networks to track carbon-bearing constituents and radiative transfer to determine the excitation of different energy levels identify the $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine structure line of ionized carbon, [C II], at a wavelength of 158 $\mu$m, as a key tracer of the cloud assembly process (Franck et al. 2018; Clark et al. 2019). Specifically, in the conditions in which the H-to-H$_2$ transition occurs, [C II] emission can trace the distribution and kinematics of the cold, neutral atomic gas and the layer of gas where hydrogen is mostly in the H$_2$ phase but the abundance of CO is low—making its rotational lines very faint or undetectable (hereafter dark CO gas). Clark et al.
(2019) identify two kinematic features in the [C II] components that indicate the presence of a converging flow. These features depend on the initial conditions of the flows—specifically, the approaching head-on velocities, which they set at $\pm 3.75 \, \text{km s}^{-1}$ corresponding to a combined collisional velocity of $7.5 \, \text{km s}^{-1}$. First, they predict faint [C II] emission from the cold, atomic neutral gas that carries the velocity information about the converging flow. The velocity offset of this emission is predicted to be $2-4 \, \text{km s}^{-1}$ from the velocity of CO emission seen in their simulation. Second, like the CNM gas, the CO-dark component of [C II] emission is spatially distributed outside of the more strongly self-shielded CO-emitting cloud, but its velocity corresponds more closely with the velocity interval of the CO emission.

In this investigation, we examine the role of converging atomic flows in the formation of the compact molecular cloud BKP 7323 (Brunt et al. 2003) with new imaging observations of [C II] 158 $\mu$m and archival data of CO $J = 1-0$ line emission, and H I 21 cm emission. At a Galactic latitude of 4°24 and located beyond the solar circle, BKP 7323 is well isolated both spatially and kinematically from any foreground and background molecular clouds. This isolation facilitates the identification of large-scale atomic gas flows associated with the cloud that may be present. Brunt et al. (2003) estimate the molecular mass of the cloud to be $1100 \, M_\odot$, assuming a CO-to-H$_2$ conversion factor of 4.3 $M_\odot/(\text{K km s}^{-1} \, \text{pc}^2)$ (Bolatto et al. 2013) and a distance of 3.23 kpc (Ragan et al. 2012). Under the designation ISOSJ 22478-6357, this region has been the target of several previous studies investigating the early stages of star formation activity (Hennemann et al. 2008; Ragan et al. 2012; Beuther et al. 2021).

2. Data

2.1. [C II] Emission

[C II] observations were obtained on the dates 2021 February 23 and 25 and March 5 as part of Stratospheric Observatory for Infrared Astronomy (SOFIA) Cycle 8 program 08-0062 using the dual polarization, double sideband, $2 \times 7$ pixel upGREAT Low Frequency Array (LFA) that operates between 1.8 and 2.5 THz (Risacher et al. 2016). The backends were fast Fourier transform spectrometers developed at the Max-Planck-Institut für Radioastronomie in Bonn (Klein et al. 2012). These provide 4 GHz of bandwidth per pixel and a maximum of 142 kHz spectral resolution corresponding to $630 \, \text{km s}^{-1}$ and $0.022 \, \text{km s}^{-1}$ velocity coverage and resolution, respectively, at the frequency of the [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine structure line. Data were calibrated approximately every 5 minutes using measurements of the sky, and hot and cold loads. Atmospheric transmission is estimated from the fits of atmospheric model brightness to the observed, calibrated sky-hot spectrum (Guan et al. 2012). Calibration uncertainties are estimated to be 20% with the atmospheric transmission uncertainty contributing the largest error of 15% (Risacher et al. 2016). Telluric lines were present in our spectra but at velocities far displaced from our target and did not impact our science analysis and interpretation. At the wavelength of the [C II] line, the half power beamwidth of our data is $14''$. Pointing and focus observations are taken at the beginning of each flight series. During the flight, optical star pointing with three guide cameras are used to maintain the stellar pattern in their respective fields of view.

This procedure provides telescope pointing and tracking accuracy of $1''$.

On-the-fly (OTF) scans were made along the Galactic longitude and latitude axes to form a cross pattern with overlap in coverage in the central region. The array was rotated by 19°1 with respect to the scanning direction to provide equal spacing along an OTF scan. A second scan was executed in the reverse direction following a shift of 5°5 perpendicular to the scanning direction to achieve full sampling. The antenna scanning speed was 5°5 s$^{-1}$ and each scan length was 126°5. These scans were repeated multiple times (44 to 72) to improve the sensitivity.

The data were processed with the GREAT pipeline at the Max-Planck Institute for Radioastronomy. This included first-order baseline subtraction and coadding spectra. All coadded spectra were smoothed to a spectral resolution of 0.25 km s$^{-1}$. Antenna temperatures were corrected for main beam efficiencies that range from 0.63 to 0.69 for the upGREAT/LFA beams placing the spectra on the mean beam temperature scale. The median rms per spectral channel over the coadded map is 0.22 K in main beam temperature units.

2.2. Molecular Line Emission

$^{12}$CO $J = 1-0$ data for BKP 7323 were extracted from the FCRAO survey of the outer galaxy (Heyer et al. 1998). The angular resolution of the survey data, sampled every 50'', is 45'', with spectral resolution 0.81 km s$^{-1}$ per channel. The median sensitivity per channel is 1 K in main beam temperature units. For this study, we smoothed the data to 60'' angular resolution and 1 km s$^{-1}$ spectral channels, which provides a median rms of 0.63 K in main beam temperature units.

2.3. H I 21 cm Line Emission

Spectroscopic data cubes of H I 21 cm line emission from the Canadian Galactic Plane Survey collected by the Dominion Radio Astronomical Observatory (Taylor et al. 2003) were obtained from the Canadian Astronomical Data Centre. The angular and spectral resolutions of these data are 1'' and 0.82 km s$^{-1}$, respectively. The rms noise in brightness temperature is 3–4 K per spectral channel.

3. Results

The spectral line data presented in this study provide information on the distribution and kinematics of both molecular and atomic interstellar gas. Figure 1 shows three representations of the data for each spectral line. From left to right we display the velocity-integrated emission, the Galactic longitude–velocity image with spectra averaged over the Galactic latitude range covered, and the Galactic latitude–velocity image with spectra averaged over the Galactic longitude range covered. For [C II] and $^{12}$CO, the velocity interval of the integration is $-43$ to $-38 \, \text{km s}^{-1}$. For the H I 21 cm data, the integration interval is $-55$ to $-35 \, \text{km s}^{-1}$.

The gas column density distributions are encapsulated in the integrated intensity images of [C II], CO, and H I 21 cm. [C II] emission is widespread throughout the cross area of the map with 79% of the observed [C II] spectra detected with integrated intensity signal to noise greater than three. Peak brightness temperatures range from 1 to 6.5 K. The very evident bright [C II] feature centered at (l,b) = (109°873, 4°267) or (α,δ) = 22°47′54″.3, 63°57′39.3″), is coincident with the peak of the extended dust emission seen at shorter ($<250 \, \mu$m).
wavelengths (Hennemann et al. 2008; Ragan et al. 2012). This is distinct from the peak of the $^{12}$CO emission which, as seen in Figure 1, peaks at $(l, b) = (109^\circ.85, 4^\circ.26)$ or $(\alpha, \delta) = (22^h47^m44^s, 63^\circ 56'39'')$. The remaining emission is fainter and more smoothly distributed within the cross-scan coverage.

At $\sim 1^\prime$ angular resolution, the molecular gas distribution from CO appears centrally peaked on the 850 $\mu$m clump (Di Francesco et al. 2008) and, as previously described, offset from the peak of [C II] emission. The peak column density of molecular gas is $1.2 \times 10^{22}$ cm$^{-2}$ assuming a CO-to-H$_2$ conversion factor of $2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. The peak H$_2$ column density from the SCUBA dust emission is $6.5 \times 10^{22}$ cm$^{-2}$. This value assumes a dust temperature of 12 K and a dust emissivity index of two. Given the uncertainties in both methods of column density determination, this is acceptably consistent.

The HI 21 cm line emission is displayed over the same area as the [C II] and CO images with a color stretch beginning at 800 K km s$^{-1}$ which corresponds to a column density of $1.5 \times 10^{21}$ cm$^{-2}$ assuming $N_H = 1.823 \times 10^{18} f T_B dV$ cm$^{-2}$, where $T_B$ is the HI brightness temperature. The atomic gas is extended throughout the displayed field but shows a localized peak coincident with the CO emission maximum, with an atomic hydrogen column density of $2 \times 10^{21}$ cm$^{-2}$.

The relative kinematics of each spectral line are accessible in the position–velocity images shown in the second and third columns of Figure 1. The brightest HI 21 cm line emission is distributed over velocities $-49$ to $-43$ km s$^{-1}$ with a peak at velocity $-45$ km s$^{-1}$. This peak velocity is blueshifted by $\sim 4$ km s$^{-1}$ relative to the peak velocity of [C II] and CO emission of $-40.5$ km s$^{-1}$.

4. Tracing CNM with [C II] emission

The spatial and kinematic relationships between the atomic and molecular gas components are key factors in evaluating the role of converging flows of atomic gas in the formation of molecular clouds. Given the total collisional velocity of 7.5 km s$^{-1}$ in the simulations, Clark et al. (2019) found that converging flows of cold, neutral atomic gas could be evident in [C II] emission within velocity intervals displaced several km
absorption occurs over the velocity interval \([-48, -42]\) km s\(^{-1}\) and indicates the presence of cold, neutral, atomic gas in the vicinity of the BKP 7323 molecular cloud.

The absorption feature occurs over the velocity interval \([-48, -42]\) km s\(^{-1}\) and the H I 21 cm spectrum toward the extragalactic continuum source shown in Figure 2 as well as the H I 21 cm spectrum at the position of the extragalactic source G109.65 +4.24 (filled in gray) and at the offset position at \(l = 109\degree 70, b = 4\degree 24\). The absorption feature occurs over the velocity interval \([-48, -42]\) km s\(^{-1}\) and indicates the presence of cold, neutral, atomic gas in the vicinity of the BKP 7323 molecular cloud.

To further quantify faint signal from ionized carbon, we fit a two-component Gaussian profile to the average [C II] spectra displayed in Figure 3 with Bayesian regression using the `emcee` package (Foreman-Mackey et al. 2013). The first Gaussian component accounts for the bright [C II] emission at \(-40.5\) km s\(^{-1}\) associated with the photodissociation regions (see section 5) while the second Gaussian component describes the weak [C II] emission at \(-45\) km s\(^{-1}\).

From the fitted Gaussian parameters of the wing emission, we derive the volume density of the atomic gas that is required to account for the observed [C II] integrated intensity given the column density of ionized carbon. Assuming the [C II] emission comes exclusively from the atomic gas component in this velocity interval, the ionized carbon column density is estimated from the hydrogen column density derived from the H 121 cm line emission using

\[
N(C^+) = [C/H]1.823 \times 10^{18} \int T_B(v)dv,  \tag{1}
\]

where the integral is over the velocity interval \(-50\) to \(-43\) km s\(^{-1}\) and [C II] is the carbon to hydrogen abundance ratio. A [C/H] value of \(1.6 \times 10^{-4}\) is adopted based on the results of Sofia et al. (2004). We use Equation (48) for the [C II] fine structure line collisional deexcitation rate for collisions with atomic hydrogen from Goldsmith et al. (2012) to derive the critical density of the [C II] line, \(n_r = 3030(T_k/100)^{0.14}\) cm\(^{-3}\). Then, using Equation (2) of Langer et al. (2010), which relates integrated [C II] intensities to column densities assuming optically thin emission, we obtain

\[
n(H^0) = \frac{3.03 \times 10^5(100/T_k)^{0.14}}{2\exp(-91.2/T_k)(3.43 \times 10^{-16}X - 1) - 1} \text{ cm}^{-3},  \tag{2}
\]

where \(X = N(C^+)/W([\text{C II}])\); \(W([\text{C II}])\), is derived from the definite integral of the Gaussian over all velocities

\[
W([\text{C II}]) = (2\pi)^{1/2}T_2\sigma_{v,2},  \tag{3}
\]

and \(T_2\) and \(\sigma_{v,2}\) are the amplitude and velocity dispersion of the second Gaussian component. In practice, we calculate a distribution of \(n(H^0)\) values for each averaged spectrum by propagating values from the posterior distributions of \(T_2\) and \(\sigma_{v,2}\) through Equations (3) and (2). A kinetic temperature of 100 K is assumed. The derived volume density profiles through the horizontal and vertical arms of the map (Figure 1, upper left) are shown in Figure 5. The mean density of all points is \(67\) cm\(^{-3}\).

The [C II] brightness temperatures, derived hydrogen volume densities, and velocities that agree with that of the H 121 cm absorption point to CNM gas in the vicinity of the BKP 7323 molecular gas. This atomic gas is kinematically displaced from the CO-emitting material by \(-4\) km s\(^{-1}\). In Section 6, we discuss the possible origins of this component and its relationship to the molecular gas of BKP 7323.
5. Photodissociation Region Conditions in the Cloud

The bright $[\text{C II}]$ lines from BKP 7323 and their alignment in velocity with the CO lines between $-43$ and $-38$ km s$^{-1}$ point to an origin from photodissociated gas within the cloud. While the cloud is far removed from any strong sources of UV radiation, newborn stars within the cloud are likely responsible for the dissociating photons. Ragan et al. (2012) identify seven protostellar cores from Herschel PACS imaging with luminosities ranging from 5 to 10 L$_{\odot}$. Six of these sources reside within the dense submillimeter clump found by Hennemann et al. (2008) while one source (ISOSS J22478+6357 ID = 7) is coincident with the peak of $[\text{C II}]$ emission and the peak position of mid infrared dust emission (Ragan et al. 2012). Recent high resolution imaging of the 1.1 mm dust continuum emission with NOEMA show 15 fragments within the clump that indicate a developing small cluster of protostars (Beuther et al. 2021).

The measured intensities $I_{\text{C II}}$, $I_{\text{CO}}$, and the ratio $I_{\text{C II}}/I_{\text{CO}}$ can provide constraints to the gas conditions within the photodissociation regions (PDRs). We first convert the integrated intensity of each spectrum from units of K km s$^{-1}$ to units of ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ using the factor, $2k_B/\lambda^3$, where $k_B$ is the Boltzmann constant and $\lambda$ is the wavelength of the $[\text{C II}]$ fine structure transition. This conversion is appropriate for a uniform source filling a diffraction-limited beam. To evaluate the above quantities, we convolve and resample the $[\text{C II}]$ antenna temperatures to the angular resolution and sampling of the $^{12}\text{CO}$ data.

The PDR Toolbox (Pound & Wolfire 2008) compiles a set of PDR models for a range of interstellar radiation field intensities, volume densities, and metallicities. The calculations

![Figure 3. $[\text{C II}]$ spectra averaged over 60 pixels along the horizontal (left) and vertical (right) cuts of the cross map. Blueshifted wing emission over the interval $-50$ to $-43$ km s$^{-1}$ (filled in gray) is evident. Angular offsets from the center of the map are shown in each spectrum. The measured brightness temperatures and velocity overlap with the absorption feature shown in Figure 2 suggest that this $[\text{C II}]$ wing emission reflects CNM gas that is present throughout the BKP 7323 cloud.](image-url)
include excitation and radiative transfer to produce model [C II] and \(^{12}\)CO intensities and ratios. We examine model wk2006 from the PDR Toolbox, which assumes a metallicity \(Z = 1\) and spans the range of incident UV flux from \(10^{-0.5}\) to \(10^{6.5}\) Habings and cloud densities \(10^{1}\) to \(10^{7}\) cm\(^{-3}\). The full set of model parameters are listed in Table 1 of Kaufman et al. (1999). The model [C II], \(^{12}\)CO intensities, and \(I_{\text{CII}}/I_{\text{CO}}\) values are shown as images in Figure 6 for a range of radiation field intensities, \(G_\alpha\) in Habing units, and gas volume densities, \(n_{\text{H}}\). The contours show the 3\(\sigma\) detection limit and the maximum value for each line (Figures 6(a) and (b)) and their ratio (6(c)) from our data. The shaded area in Figure 6(d) shows the range of \(\log(G_\alpha)\) and \(\log(n_{\text{H}})\) where these measured extremes overlap. It covers the range of radiation field intensity \(0.5 < \log(G_\alpha) < 1.5\) and volume density range \(10^2\) cm\(^{-3}\) < \(n_{\text{H}}\) < \(10^4\) cm\(^{-3}\). The range of allowable \(G_\alpha\) and \(n\) is reasonable given the moderate luminosities from the developing protostellar cores identified by Ragan et al. (2012) and the volume densities probed by the \(^{12}\)CO \(J = 1\rightarrow 0\) transition.

6. Discussion

Our [C II] observations have identified a faint emission component that is kinematically offset from the velocity of CO emission from the BKP 7323 molecular cloud. We attribute this component to CNM atomic gas based on the match between its velocity and that of a nearby H\(1\,21\,cm\) absorption feature, the derived volume densities, and the measured [C II] brightness temperatures that are similar to those predicted for CNM conditions. However, the physical relationship of this material to the molecular cloud is difficult to determine unambiguously. This component could simply be a distinct CNM cloud that has no physical connection to BKP 7323. Yet, the H\(1\,21\,cm\) emission at this velocity has a local maximum at the position of the cloud, which is circumstantial evidence of a physical association. If related to the molecular cloud, it is unlikely that this component arises from a low column density, atomic envelope. To remain bound to the central, molecular cloud, the velocity of the envelope with respect to the CO velocity should be comparable to the virial velocity dispersion of the cloud. For a spherical cloud with uniform density and neglecting surface pressure and magnetic pressure terms, the virial velocity dispersion is \((GM/S)^{1/2}\) (McKee & Zweibel 1992). The molecular mass of BKP 7323 is \(1100\,M_\odot\), and its radius is 3 pc. So its virial velocity dispersion is 0.6 km s\(^{-1}\), which is far less than the measured 4 km s\(^{-1}\) displacement of this component from the molecular gas velocity. Low density atomic gas that might be present in an envelope of the molecular cloud thus would rapidly separate from the cloud with diameter \(L\) within a crossing time, \(L/\delta v \sim 1.5\) Myr.

The absence of CO emission in this blueshifted interval (see Figure 4), could indicate that the [C II] emission arises from a dark-CO component, where H\(_2\) is present but CO emission is not detectable owing to very low CO abundance (Wolfire et al. 2010). However, based on the numerical simulations by Clark et al. (2019), the velocity of a dark-CO component is expected to be comparable to the velocity of CO emission. The 4 km s\(^{-1}\) velocity offset of the [C II] blueshifted emission from the CO velocity indicates that the [C II] emission is not from a CO-dark component of gas.

We propose that this emission component at \(V_{\text{LSR}} \sim -45\) km s\(^{-1}\) represents a large-scale flow of CNM material that is streaming onto the molecular cloud. But the question whether this flow is one part of a two stream, converging flow remains. Ideally, a signature of converging flows onto a developing molecular cloud would be a farside, blueshifted component and a nearside, redshifted component relative to the bulk velocity of the molecular cloud as implied by the simulations by Clark et al. (2019). However, it is improbable that most converging flows are head-on collisions as modeled in the simulations. Our observations find no evidence for [C II] emission over the velocity interval \(-40\) to \(-35\) km s\(^{-1}\) that would confirm the presence of a redshifted counterpart to the observed blueshifted gas flow indicated by the wing seen in Figure 3. To examine the atomic gas directly over a larger area, we show images of the H\(1\,21\,cm\) line emission integrated over the \(V_{\text{LSR}}\) intervals \([-50, -43]\), \([-43, -38]\), and \([-38, -31]\) km s\(^{-1}\) in Figure 7. The redshifted interval \([-38, -31]\) km s\(^{-1}\) shows faint H\(_1\) emission with \(W(H\,1) < 200\) K km s\(^{-1}\) with no apparent connection to the CO cloud. This emission mostly likely represents diffuse WNM gas that is not interacting with BKP 7323.
HI emission in the \([-43, -38]\) km s\(^{-1}\) velocity range is spatially coincident with the molecular cloud and extends to higher Galactic latitudes beyond the molecular cloud edge as traced by CO emission. All or part of this feature may be related to the atomic envelope of the molecular cloud. If a fraction of this atomic gas is streaming toward the molecular cloud as part of a counterpart, secondary flow, its motion would be in the plane of the sky. However, such a streaming component would not be identified in [C II] measurements as the bright emission from the PDR would greatly exceed the faint signal from the hypothetical CNM flow within the same velocity interval. Alternatively, the blueshifted component of CNM gas in the \([-50, -43]\) km s\(^{-1}\) interval that is observed could be a singular flow onto the developing molecular cloud with no counterpart flow of atomic gas. This component is brighter in H\(1\) 21 cm line emission than the other components and provides a larger reservoir of material that could be incorporated into the molecular cloud.

Taking the properties from the singular flow that we actually measure in the blueshifted interval, the rate of atomic mass falling onto the cloud can be estimated as

\[
dM/dt = \rho v_{\text{flow}} L^2 = n(H^0)\mu_H m_H v_{\text{flow}} L^2, \tag{4}
\]

where \(\rho\) is the mass volume density, \(v_{\text{flow}}\) is the flow velocity, and \(L\) is the physical size of the cloud. For \(n(H^0)=67\) cm\(^{-3}\), \(v_{\text{flow}}=4\) km s\(^{-1}\), and \(L=6\) pc, \(dM/dt=3.2 \times 10^{-4} M_\odot\) yr\(^{-1}\). At this mass flow rate, it would take 3.4 Myr to build up the current 1100 \(M_\odot\) mass of the cloud.

This timescale to form a molecular cloud or a clump within a larger cloud complex is a reasonable estimate with respect to computational simulations of converging flows (Clark et al. 2012; Vázquez-Semadeni et al. 2017; Clark et al. 2019). In these studies, H\(_2\) and CO molecules form within the dense regions generated by the shocks of the converging flows or within the ensuing thermal instabilities. But this occurs in the later stages—10–16 Myr after the initial interaction of the atomic gas flows as tracked by the simulations with low combined velocity collisions. This timescale is compatible with the 3.4 Myr formation time of BKP 7323.

BKP 7323 is a small, low mass molecular cloud so its formation may not be representative of giant molecular clouds with masses greater than \(10^5 M_\odot\). Its spatial and kinematic isolation from other CO-emitting clouds precludes its having formed by the agglomeration of smaller, existing molecular clouds. Rather, the location of BKP 7323 in the outer galaxy, where the molecular gas fraction is low, suggests that it condensed directly from the neutral atomic gas component of the interstellar medium (Koda et al. 2016). Our [C II] measurements and H\(1\) 21 cm data identify a stream of cold, neutral atomic gas onto BKP 7323 that supports the top-down model of molecular cloud formation and growth in the outer galaxy.

7. Conclusions

Observations of the [C II] line from the compact molecular cloud BKP 7323 show bright emission that likely arises from the photodissociated gas resulting from embedded star

\[ \text{Figure 6.} \quad \text{PDR Toolbox models of line emission. (a) Image of the logarithm of [C II] intensities over a range of radiation fields and gas densities. The red lines show contours of the logarithms of the observed 3σ detection limit (−5.14) and maximum [C II] intensity (−4.14) (in units of ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}). (b) Same as (a) for }^{12}\text{CO emission. Contours are the logarithm of the observed 3σ detection limit (−7.98) and maximum intensity of }^{12}\text{CO emission (−7.02). (c) Same as (a) for the ratio [C II]/^{13}\text{CO. Blue lines denote the logarithms of the 3σ} (2.42) and maximum (3.41) ratio values. (d) Same contours in (a), (b), and (c). The gray shading marks subset area bounded by the contours of acceptable values of } I_{\text{C II}}, I_{12\text{CO}}, \text{ and } I_{\text{C II}}/I_{12\text{CO}}. \text{ This area provides the range of model radiation field and gas density values that are consistent with the observations.} \]
formation activity within the cloud. Spatial averaging of the data reveals a weak secondary emission component that we attribute to cold, neutral atomic gas based on brightness of the C II, its having the same velocity interval as the nearby H I 21 cm absorption feature, and the derived atomic gas mean volume density of 67 cm$^{-3}$. The velocity of this component is blueshifted from the molecular cloud by $\sim$4 km s$^{-1}$, which suggests that this feature is atomic material owing onto the molecular cloud with a mass infall rate of $3.2 \times 10^{-3}$ $M_\odot$ yr$^{-1}$. Such atomic gas streams may provide an important reservoir of material to form molecular clouds and accumulate mass.

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Facility: SOFIA (GREAT).
Software: astropy (Astropy Collaboration et al. 2013), emcee (Foreman-Mackey et al. 2013), PDR Toolbox (Kaufman et al. 2006; Pound & Wolffre 2008).

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