G5.89: An Explosive Outflow Powered by a Proto-Stellar Merger?

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ABSTRACT

The explosive outflows are a newly-discovered family of molecular outflows associated with high-mass star forming regions. Such energetic events are possibly powered by the release of gravitational energy related with the formation of a (proto)stellar merger or a close stellar binary. Here, we present sensitive and high angular resolution (0.85″) archival CO(J=3-2) observations carried out with the Submillimeter Array (SMA) of the high-mass star forming region G5.89−0.39 that reveal the possible presence of an explosive outflow. We find six well-defined and narrow straight filament-like ejections pointing back approximately to the center of an expanding molecular and ionized shell located at the center of this region. These high velocity (−120 to +100 km s⁻¹) filaments follow a Hubble-like velocity law with the radial velocities increasing with the projected distance. The estimated kinematical age of the filaments is about of 1000 yrs, a value similar to the dynamical age found for the expanding ionized shell. G5.89 is the thus the third explosive outflow reported in the galaxy (together with Orion BN-KL and DR21) and argues in favor of the idea that this is a frequent phenomenon. In particular, explosive outflows, in conjunction with runaway stars, demonstrate that dynamical interactions in such groups are a very important ingredient in star formation.

Key words: instrumentation: high angular resolution – techniques: imaging spectroscopy – stars: formation – ISM: individual objects (G5.89−0.39)

1 INTRODUCTION

G5.89−0.39 or W28 A2 (hereafter G5.89) is an expanding shell-like Ultracompact HII (UC HII) region (Wood & Churchwell 1989) at a distance of 2.5⁻⁰.¹⁹ ± 0.₁₇ kpc (Sato et al. 2014). This measure is inconsistent from that obtained in Motogi et al. (2011) using similar techniques (1.28⁻⁰.₀⁹ ± 0.₀₈ kpc), however, the value obtained by Sato et al. (2014) seems more reliable since they used two different background sources limiting the potential position errors of the masers as is described in their study. The UC HII region is about 0.1 pc (7″) in size, and its dynamical age is 600⁻²₂₅₀ years, estimated from the angular expansion rate (Acord et al. 1998). Combining a model for the nebular emission and H radio recombination line spectra, Acord et al. (1998) estimated an expansion velocity for the UCHII region of about 35 km s⁻¹. Near infrared NACO-VLT observations carried out by Feldt et al. (2003) revealed that G5.89 contains a young O5 V star, which they proposed to be the exciting source of the UC HII region. This young star, however, is located about 1″ to the northwest from the center of the shell-like UC HII region. Puga et al. (2006) also reported an ionized outflow traced by the Brγ emission located in the northeast side of the UC HII region.
This outflow is likely tracing the presence of a second object associated with the region. There are also a group of (sub)millimeter compact sources located in the vicinities of the UC HII region (Sollins et al. 2004; Su et al. 2012). However, as it is discussed in Hunter et al. (2008), some of them could not be heated internally.

It is also interesting to note that there are also many X-ray energetic sources, far infrared and a GeV to gamma-ray source (HESJ1800-240B) associated with G5.89 (Hampton et al. 2016; Gusdorf et al. 2015; Leurini et al. 2015). In particular, far-IR spectroscopic Herschel observations obtained by Karska et al. (2014) revealed high-J CO lines where most of the CO luminosity from these outflows is possibly radiated.

G5.89 is associated with high-velocity (−75 to +75 km s$^{-1}$) outflowing gas originally identified in CO and CS by Harvey & Forveille (1988). The outflow emission has been subsequently studied using single-dish CO and SiO (Klaassen et al. 2006) and interferometric CO, HCO$^+$, and SiO (Watson et al. 2007; Sollins et al. 2004) observations. Klaassen et al. (2006) proposed that the outflow located in this region is possibly a fossil flow (that is, a flow without a present excitation source but that continues moving by momentum conservation) with an age of about 1000 yrs. The reported position angle of the outflow is notably different between the tracers, being nearly east-west in CO and HCO+ (position angle +84°), vs. northeast-southwest in SiO (position angle +30°). The origin and relation of these different outflows remain poorly understood. Moreover, the powerful SiO bipolar outflow reported by Sollins et al. (2004) may be a remanent outflow ejected possibly from Feldt’s infrared star or some other protostars in the vicinity of the UCHII region. This is because recent SMA high angular observations resolved both lobes (see Figure 8 from Hunter et al. 2008). On the other hand, the outflows reported in this region are massive and very energetic. For example, Harvey & Forveille (1988) reported that the outflow located in this region is about 1000 times more energetic ($\sim 10^{49}$ erg) than the one located in Orion-KL ($\sim 10^{46}$ erg). For the case of the outflow in Orion-KL, Goicoechea et al. (2015) reported that the L$_{CO}$/L$_{bol}$ luminosity ratio in this region is quite different compared to other high-mass SFRs, making the Orion-KL outflow peculiar.

More recently, using interferometric SMA sensitive observations Su et al. (2012) reported extremely high-velocity (−150 to +80 km s$^{-1}$) outflowing gas in CO (J=2-1) and (J=3-2) associated with the shell-like UC H II region. These high velocity lobes were interpreted as belonging to two dif-
different outflows. In addition, the outflow lobes clearly show a Hubble-like kinematic structure. A diagram of the estimated temperature of the outflowing gas vs. their radial velocity of the molecular lobes presented in Figure 4 of Su et al. (2012) showed that the temperature increases with the radial velocities and projected distances. This result suggests that the outflowing gas is warmer on the tips possibly as a result of strong shocks with the interstellar medium.

The explosive outflows are a new family of molecular outflows associated with high-mass star forming regions (Zapata et al. 2009, 2013a; Bally 2016; Bally et al. 2017). Such energetic events are possibly powered by the release of gravitational energy related with the formation of a (proto)stellar merger or a close stellar binary (Bally & Zinnecker 2005; Zapata et al. 2017; Bally et al. 2017). At this moment, there are four clear morphological and kinematical differences between the classic protostellar and the newly-discovered explosive molecular outflows that are described in Zapata et al. (2017):

- The explosive outflows consist of narrow straight filament-like ejections or streamers with different directions and in almost an isotropic configuration.
- The narrow molecular filaments point back to approximately an explosion site.
- The outflow presents a very-well-defined Hubble flow-like increase of velocity with distance from the origin in the explosive filaments.
- The overlapping of the redshifted components with respect to the blueshifted components.

In this paper, using archival SMA high angular resolution (~0.8″) CO(J=3-2) observations and following the characteristics of the explosive outflows described in Zapata et al. (2017), we propose the possible presence of an explosive outflow in G5.89 centered in the expanding ionized and molecular shell-like structure found in this region. In the next sections, we describe in more detail our findings on this remarkable region.

2 ARCHIVAL OBSERVATIONS

The SMA observations were carried out in 2006 June 05 using its extended configuration. At that time, the array was with its eight antennas. The 28 independent baselines in this configuration ranged in projected length from 15 to 233 k.l. The phase center of the observations were situated at the position $\alpha_{J2000.0}=18^h 00^m 30^s.2$, $\delta_{J2000.0}=-24^\circ 04^\prime 00^\prime\prime.5$. The SMA primary beam is approximately $30^\prime$ at 345 GHz. This allowed us to study the entire outflow in G5.89 with a single pointing. In these observations, we did not merge the SMA data with short-spacing observations (single-dish) because we were interested in the high-velocity compact emission from the CO, and not with the extended systemic emission.

The digital correlator was set to have 24 spectral "chunks" of 104 MHz and 128 channels each. This spectral resolution yielded a velocity bin width of about 0.7 km s$^{-1}$. However, we smoothed this to 7 km s$^{-1}$ given the very broad CO line present in G5.89, see Su et al. (2012). The observations were centered at a frequency of 346.48 GHz in the upper side band, while in the lower side band was at 336.48 GHz. The CO(3-2) line was detected at a rest frequency of 345.81 GHz. The total available double-sideband bandwidth was 4 GHz.

The quasars J1733–130 and J1911–201 were used as gain calibrators, while Jupiter's moon Callisto and the dwarf planet Ceres were used as bandpass and flux calibrator, respectively. The uncertainty in the flux scale is estimated to be between 15% and 20%, based on the SMA monitoring of quasars.

The data were calibrated using the IDL superset MIR adapted for the SMA. The calibrated data were then imaged and analyzed in standard manner using MIRIAD (Sault et al. 1995) and CASAPy (McMullin et al. 2007). We also used some routines in Python to image the data (Astropy Collaboration et al. 2013). More technical specifications of the SMA and its calibration strategies can be found in Ho et al. (2004).

A 12CO(J=3-2) spectral velocity cube was obtained setting the ROBUST parameter of the task INVERT to +2 to obtain a better sensitivity. The contribution from the strong continuum was subtracted using the MIRIAD task uvlin. The resulting r.m.s. noise for the line cube was about 30 mJy beam$^{-1}$ per velocity channel, with a beam with an angular resolution of 0″9 × 0″8 with a P.A. = −10°. In this paper, we concentrate in the CO(J=3-2) line emission from G5.89, the continuum and some other lines present in the observations (e.g. SO, SO$_2$ and H$_2$CO) are mostly associated with the ionized shell. We refer to the author to Hunter et al. (2008), where a very dedicated SMA study is presented of these structures.

3 RESULTS

The CO filament-like structures revealed in our Figures 1 and 2 were obtained from the maps in velocity windows of 7 km s$^{-1}$ width presented in the Appendix. In these velocity channels maps we found about one hundred localized emission features. The position and radial velocities of these condensations were then obtained using linearized least-squares fits to Gaussians ellipsoids using the task SAD of AIPS. This is a similar procedure to that used by Zapata et al. (2009, 2013a,b). We discerned about six molecular filaments that show consistent velocity increments and they are presented in Figures 1 and 2. It is important to mention that we do not detected more molecular structures other than the filament-like objects.

In Figure 1, we present the most prominent high-velocity CO(J=3-2) features outside of the velocity window from −50 to +40 km s$^{-1}$, overlaid on a NACO/VLT “L” band infrared image (Feldt et al. 2003) of G5.89. Within this velocity window the radiation arises basically from the ambient cloud (and probably some other molecular clouds close

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2 The raw data can be obtained from: http://www.cfa.harvard.edu/

3 The MIR-IDL cookbook by C. Qi can be found at http://cfa-www.harvard.edu/cgi/mircook.html.
to the galactic plane given the broad range of velocities) and is spatially extended, thus cannot be completely reconstructed by the Submillimeter Array. The infrared image is tracing a shell-like structure that is associated with the expanding UCHII region at the center of G5.89. Additionally, we also include in this image the positions of the two objects located in the vicinities of the infrared shell, the Feldt and Puga objects reported in Feldt et al. (2003) and Puga et al. (2006), respectively. The compact infrared source in the middle of the rectangle is probably part of the shell, the H/Kα/L′ image from Feldt et al. (2003) does not reveal any massive young object. Here, the L′ (3.8 μm) is tracing emission from warm dust from the shell and the possibly from the disk of the Feldt’s star.

Receding CO emission shows radial velocities up to +90 km s$^{-1}$, while approaching (blueshifted) radial velocities reached −110 km s$^{-1}$. This is in very good agreement with the SMA observations of Su et al. (2012). However, in our observations with better angular resolution (a factor of almost 3 better than the previous SMA observations) all the CO condensations were much better resolved angularly into narrow filament-like structures (Figure 1). Every CO gas condensation reported in Figure 2 of Su et al. (2012) has a counterpart in the form of a filament-like structure. The most northern redshifted condensation was resolved into two filaments. In total, we report the presence of six straight and narrow filaments, three redshifted and three blueshifted pointing approximately to the center of the infrared shell at the position $\alpha_{2000.0}=18^h00^m30^s.3 \pm 1.0''$ and $\delta_{2000.0}=-24^\circ04'01''5 \pm 1.0''$. This position corresponds approximately to the center of the infrared and radio shell reported in Feldt et al. (2003); Acord et al. (1998), see Figure 1. We fitted very carefully straight lines to every filament and extrapolate them to find this position in the sky. Note that none of these molecular filaments points directly to the infrared and optical sources located in the surroundings of the UC HII region.

A projected distance vs. radial velocity diagram of the six straight filaments reported in this study is presented in Figure 2. This diagram reveals the kinematics of the molecular filaments. Each filament follows a Hubble velocity law, that is, the radial velocity along every filament changes linearly with on-the-sky distance from this center. Moreover, all filaments seem to converge to the single radial velocity of about 9 km s$^{-1}$. This velocity is approximately the systemic velocity of the cloud in G5.89, see Su et al. (2012).

4 DISCUSSION

All physical and kinematical features found on this outflow are reminiscent of those observed in two previously known explosive outflows: Orion-KL and DR21, see Zapata et al. (2017); Bally (2016). The flow found in G5.89 consists of narrow straight filament-like ejections with different directions. The six narrow molecular filaments point back to the approximately the same central position. This central position is devoid of known sources at different wavelengths (IR, mm, cm...), see our Figure 1. These filament-like structures present very-well-defined Hubble flow-like increase of velocity with distance from the origin, which is the center of the UCHII region. There is overlapping in the northern region between the redshifted and the blueshifted components (Hunter et al. 2008; Su et al. 2012). This overlapping can be even better discerned on the single-dish images presented in Choi et al. (1993). We therefore propose that the outflow from G5.89 is explosive.

The outflow in G5.89 however is far from being isotropic, as for example, the outflow in Orion-KL (Bally et al. 2017). This can be explained in terms of sensitivity. SMA observations of the explosive outflow in Orion-KL revealed about 40 expanding molecular filaments associated with this flow (Zapata et al. 2009), and recent ALMA observations confirmed its explosive nature with more than 150 molecular filaments (Bally et al. 2017). This difference in the number of filaments mainly lies in the tremendous sensitivity offered by the ALMA telescope, approximately a factor of about 100 improvement in line emission sensitivity as compared to the SMA. ALMA observations of G5.89 could confirm the explosive nature of the flow, and define its overall geometry.

The presence of an explosive outflow might explain some of the kinematical and morphological characteristics of G5.89. For example, the fact that this outflow is considered as a fossil outflow (Klaassen et al. 2006) is in agreement with a single and brief event that produced the molecular debris. The ionized and infrared expanding shell could also be created by this powerful event (a molecular and expanding shell structure is also associated with the explosive outflow in Orion-KL Zapata et al. 2011). Moreover, the center of the ionized UCHII coincides with origin of the explosive flow, see Figure 1 and Hunter et al. (2008), this indicated that the UC HII region could be a result of the explosion. A UCHII region at the center of the explosive outflow is not found in Orion-KL possibly because this still very embedded in large quantities of material. But, for the case of DR21, there is the presence of a large HII region (Zapata et al. 2013a) with a similar age to that of the explosion. As this ionized region

![Figure 2](image-url)
in DR21 is older (10^4 years), this is not very embedded in dust and one can see the ionized emission escaping from this region.

We thus consider that the explosive outflow in G5.89 was possibly caused by a (proto)stellar merger or the formation of a close binary as in Orion-KL (Bally 2016; Bally et al. 2017). We speculate that perhaps the O5 V young star, the Feldt’s infrared star might be involved in this kind of energetic event. Taking a mean radial velocity of 80 km s^{-1} for the outflow at a distance from the origin of 6′′ (this is a crude value for the length of the filaments), we found a kinematical age for the molecular flow of 1000 yrs, a value similar to the dynamical age found in the expanding ionized shell (600 yrs) and the fossil CO flow (1000 yrs) reported by Klaassen et al. (2006). Assuming a dynamical age of the explosion of 1000 yrs, and the distance from Feldt’s star to the center of the explosion is about 1.5″ or 4300 AU, we estimated that the velocity in the plane of the sky of this infrared star could be around 20 km s^{-1}. This is in very good agreement with the tangential velocities also in the plane of the sky of the runaway Orion stars BN, Source I, and n, see Rodríguez et al. (2017). As the Feldt’s star putative tangential velocity (20 km s^{-1}) coincides with the expanding velocity of the infrared and ionized UCHII region (35 km s^{-1}), we suggest that both objects were maybe ejected at a similar time. In this picture, both objects should coincide with a similar timescale. As the Puga’s object is also at a similar distance from the explosion center, it is suggestive that maybe this object is also related to the outflow and the UCHII region. However, we think that many more observations are needed to confirm this hypothesis.

Even when future ALMA observations could confirm our findings in G5.89, the fact that we have a third explosive outflow in the galaxy argues in favor of the idea that this is a common phenomenon happening in high-mass star forming regions. With more cases like this one discovered in different SFR will allow us to estimate more precisely the rate of massive protostellar merging, something crucial on the formation of the massive stars as is suggested by the closest high-mass SFR: Orion-KL. In particular, explosive outflows, in conjunction with runaway stars, demonstrate that dynamical interactions in such groups are a very important ingredient in star formation. Interactions and dynamics can limit accretion and therefore set the final masses of stars. N-body dynamics may be even more important in establishing the Initial Mass Function (IMF) than initial conditions. The greater the number of explosive outflows, the more important N-body dynamic is for the IMF.

We undertook an extensive search in the GAIA DR2 catalogues for the proper motions of the Feldt’s star. However, at this point there seems to be no optical counterpart for this object. Deep radio observations with the VLA/SMA have also not revealed a counterpart in these wavelengths for this object (Hunter et al. 2008).

5 CONCLUSIONS

In this paper, we have presented sensitive CO(J=3-2) archival observations from the high-mass star forming region G5.89 carried out with the Submillimeter Array (SMA). Given the good sensitivities and the sub-arcsecond angular resolution of these observations, we revealed six well-defined and narrow straight filament-like ejections pointing back approximately to the center of an expanding molecular and ionized shell located at the center of this region. These high velocity (~120 to +100 km s^{-1}) filaments follow a Hubble-like velocity law with the radial velocities increasing with the projected distance. These structures and kinematics have been reported to be present in explosive outflows as Orion-KL and DR21. We conclude that the outflow in G5.89 is explosive and could be originated by a (proto)stellar merger or maybe the formation of a close binary, where perhaps the O5 V Feldt’s star might be involved.

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Figure A1. SMA CO(J=3-2) channel velocity maps of the blueshifted emission from the outflow in G5.89. The radial velocities are indicated in the upper part of each channel. The position of the objects reported in Feldt et al. (2003) and Puga et al. (2006) are marked with a red (Feldt’s star) and yellow (Puga’s object) circle, respectively. The red rings in the center of each channel traces the position of the UCHII region, see Acord et al. (1998). The emission arising from the UCHII region at high velocities is due likely to line contamination from some other molecular species. At the corresponding rest frequency 345.929 GHz (b.e. −110 and −103 km s$^{-1}$), we identified the molecular line transition $^{34}$SO$_2$(17,14,17,15). The synthesized beam size of the image is $0''.9 \times 0''.8$ with a P.A. = $-10\degree$. The grey rings are only intended to guide the author in the position of the molecular CO condensations at different spectral channels.

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APPENDIX A: CHANNEL MAPS

Channel velocity maps of the CO(3-2) line emission obtained with the SMA from G5.89.

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Figure A2. SMA CO(J=3-2) channel velocity maps of the redshifted emission from the outflow in G5.89. The radial velocities are indicated in the upper part of each channel. The position of the objects reported in Feldt et al. (2003) and Puga et al. (2006) are marked with a red (Feldt’s star) and yellow (Puga’s object) circle, respectively. The red rings in the center of each channel traces the position of the UCHII region, see Acord et al. (1998). The synthesized beam size of the image is $0''.9 \times 0''.8$ with a P.A. = $-10\degree$. The grey rings are only intended to guide the author in the position of the molecular CO condensations at different spectral channels.