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A Highly Collimated Flow from the High-mass Protostar ISOSS J23053+5953 SMM2

Tatiana M. Rodríguez[1], Peter Hofner[1,2], Esteban Araya[3], Qizhou Zhang[4], Hendrik Linz[5], Riccardo Cesaroni[6], Stan Kurtz[7], Laura Gomez[8], Carlos Carrasco-González[7], and Viviana Rosero[9]

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[1] Physics Department, New Mexico Tech, 801 Leroy Pl., Socorro, NM 87801, USA; tatiana.rodriguez@student.nmt.edu

[2] Adjunct Astronomer at the National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA

[3] Physics Department, Western Illinois University, 1 University Circle, Macomb, IL 61455, USA

[4] Center for Astrophysics-Harvard Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA

[5] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

[6] INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

[7] Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 72-3 (Xangari), Morelia, Michoacán 58089, Mexico

[8] Joint ALMA Observatory, Alonso de Córdova 3107, Vitacura, Santiago, Chile

[9] National Radio Astronomy Observatory, 1003 Lopezville Rd., Socorro, NM 87801, USA

Tatiana M. Rodríguez https://orcid.org/0000-0003-0090-9137

Esteban Araya https://orcid.org/0000-0001-6755-9106

Qizhou Zhang https://orcid.org/0000-0003-2384-6589

Riccardo Cesaroni https://orcid.org/0000-0002-2430-5103

Stan Kurtz https://orcid.org/0000-0002-1084-6275

Carlos Carrasco-González https://orcid.org/0000-0003-2862-5363

Viviana Rosero https://orcid.org/0000-0001-8596-1756

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Abstract

We present Very Large Array cm continuum observations, as well as 1.3 mm continuum and CO(2–1) observations taken with the Submillimeter Array toward the high-mass protostellar candidate ISOSS J23053+5953 SMM2. Compact cm continuum emission was detected near the center of the SMM2 dust core, and the 1.3 mm thermal dust emission indicates a core mass of 46 $M_{\odot}$. The CO(2–1) observation revealed a large, massive molecular flow centered on the SMM2 core. This fast outflow (>50 km s^{-1}) appears highly collimated, with a broader, lower-velocity component. The large values for outflow mass (45 $M_{\odot}$), and energetics derived are consistent with those of flows driven by high-mass YSOs. The dynamical timescale of the flow is between 1.5−7.2 × 10^4 yr. Our data confirm previous findings that SMM2 is an emerging high-mass protostar in a very early phase of evolution, with an ionized jet, and a fast, highly collimated, and massive outflow.

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1. Introduction

ISOSS J23053+5953 is a high-mass star-forming region located toward the Cepheus molecular cloud complex ($d \sim 4.3$ kpc). Birkmann et al. (2007) reported two sub-mm cores in this region: SMM1 and SMM2. SMM2 is a great candidate for a high-mass protostar in a phase of rapid mass accretion, but still before the formation of a prominent hot core region. Birkmann et al. (2007) measured a core mass of 26 $M_{\odot}$ within 8000 au for SMM2, and found that it shows clear signs of mass infall at a rate of 2×10^{-3} $M_{\odot}$ yr^{-1}. The authors also estimated the age of SMM2 to be between 5×10^3 and 3.6×10^4 yr, via SED modeling.

We conducted VLA cm continuum observations toward this source at 6, 3.6, and 0.7 cm, as well as SMA molecular line observations at 230.5 GHz (1.3 mm) toward ISOSS J23053+5953 to study the nature of SMM2, a unique source in the earliest stages of high-mass stellar formation. We present here a highlights of our results.

2. Results

2.1. Continuum Emission

Our VLA observations revealed 3.6 cm continuum emission toward SMM2, which indicates the presence of ionized gas on a size scale of 1000 au, likely due to an emerging jet. Regarding the 1.3 mm dust continuum emission, we measured a total flux of 71.5 mJy, and estimated a deconvolved size of about 15,700 × 8200 au and a dust mass of 46 $M_{\odot}$. The elongation of the dust core (PA = 33$\fdg$5) is approximately perpendicular to the CO flow axis.

2.2. Molecular Emission

Our CO(2–1) observations revealed a highly collimated and fast CO outflow, together with a broader, lower velocity component. The flow is clearly associated with SMM2 and has a total projected length of about 1.45 pc. We identified three gas velocity ranges: low (LV), intermediate (MV), and high-velocity (HV). An integrated intensity (moment-0) map for each velocity component is showed in Figure 1. We can see that the LV emission appears conical and close to SMM2, while the HV emission is highly collimated and it is located further away from the source.

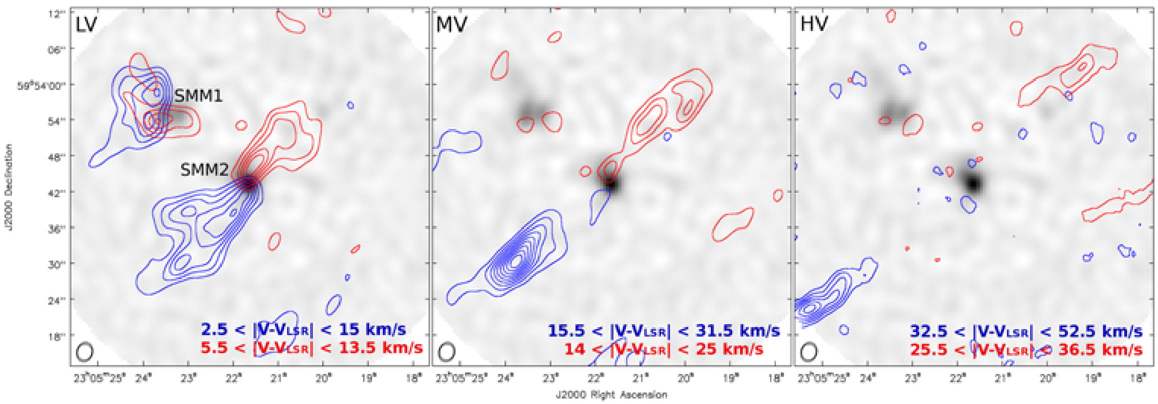

Figure 1. Integrated intensity maps of the blue- and redshifted CO(2–1) emission (contours), overlaid on the 1.3 mm continuum emission (gray scale). The intensity was integrated in three different velocity ranges: low (LV, left panel), intermediate (MV, middle panel), and high velocities (HV, right panel). In the bottom left of each panel we show the beam size of both the CO and the continuum emission.

We also detected $^{13}CO(2–1)$ and $C^{18}O(2–1)$ emission associated with SMM2. The ^{13}CO spectrum presents a velocity range not as broad as that of the ^{12}CO, while the $C^{18}O$ shows no evidence of line wings. A Gaussian fit to the $C^{18}O(2–1)$ line results in a velocity of −52.7 km s^{-1}, which we take as the systemic velocity for the SMM2 core, and a core mass of about 2 $M_{\odot}$. This value is significantly lower than the mass derived from the 1.3 mm continuum.

Following the definitions and equations in Dunham et al. (2014) and Plunkett et al. (2015), and using the LTE and optically thin approximations, we were able to estimate the CO flow mass (M_{out} = 45 $M_{\odot}$), momentum ($P_{out} = 4.3 \times 10^2$ $M_{\odot}$ km s^{-1}), energy ($E_{out} = 5.2 \times 10^{46}$ erg), characteristic velocity (V_{char} = 9 km s^{-1}), characteristic dynamical time ($t_{dyn} = 7.2 \times 10^4$ yr), mass-loss rate ($\dot{M}_{out} = 6.1 \times 10^{-4}$ $M_{\odot}$ yr^{-1}), force ($\dot{P}_{out} = 6 \times 10^{-3}$ $M_{\odot}$ yr^{-1} km s^{-1}) and luminosity ($\dot{E}_{out} = 5.9$ $L_{\odot}$).

To further study the flow kinematic, we made intensity-weighted velocity field (moment-1) and velocity dispersion (moment-2) maps of the CO(2–1) emission, integrating over (1) the LV range and (2) the MV and HV ranges combined (MV+HV). In the moment-1 map, the MV+HV emission presents a velocity increase with distance from the central source, and we also observe a change of flow angle from ~130° to about 160° in the inner 10". Regarding the moment-2 maps, the LV emission presents a large velocity dispersion toward the center of SMM2 (~8 km s^{-1}), where with our angular resolution (corresponding to about 10,000 au), both blue and red wings are observed. Thus, the flow launching zone is likely at this position. Further out in the lobes the dispersion is higher in the center of the flowing gas, and smoothly decreasing to the edges. In the moment-2 map of the MV+HV emission there is a velocity dispersion pattern that resembles a bow-shock structure in the red lobe, probably caused by interaction of the flow with the surrounding matter.

3. Analysis

3.1. Nature of the CO Outflow

The velocity increase with distance from the driving source has been interpreted with a jet-bow shock model with episodic ejection events before (e.g., Arce et al. 2007). The bow shock features observed in the moment-2 map of the MV+HV CO emission are consistent with this interpretation. We also note that the change in the flow angle observed in the MV+HV maps could be suggesting a precession of the outflowing material.

3.2. Nature of ISOSS J23053+5953 SMM2

Our results support the suggestion of Birkmann et al. (2007) that SMM2 is an extremely young high-mass protostar.

First, the outflow mass and energetics measured, which are lower limits considering the uncertainties involved, are consistent with those of flows driven by high-mass objects. Second, and as mentioned before, our VLA observations revealed a 3.6 cm source coincident in position with SMM2. At the sensitivity level of our observations ($\sigma_{3.6\,\mathrm{cm}} = 2.5\ \mu$Jy beam^{-1}), no low-mass protostar should be detected at the distance of SMM2 (see Rosero et al. 2019, Section 2.1). Furthermore, the radio luminosity of the SMM2 at 3.6 cm is $S_\nu \quad d^2 = 1.3$ mJy kpc^2, which is typical of a high-mass object (Anglada et al. 2018; Rosero et al. 2019).

Regarding the age of SMM2, the dynamical timescale we estimated for the flow ($t_{\mathrm{dyn}} = 7.2 \times 10^4$ yr) was based on the definition of characteristic velocity from Plunkett et al. (2015), i.e., $t_{\mathrm{dyn}} = R_{\mathrm{max}}/V_{\mathrm{char}}$ with $V_{\mathrm{char}} = P_{\mathrm{out}}/M_{\mathrm{out}}$. This V_{char} (~9 km s^{-1}) is low in comparison to the velocities the CO emission reaches, hence this *characteristic* dynamical time is most certainly overestimated. If instead we use the largest velocity offset of the CO emission, we obtain a dynamical timescale of $t_{\mathrm{dyn}} \sim 1.5 \times 10^4$ yr.

In addition, the large difference between the core mass estimated from the $C^{18}O$ (2 $M_\odot$) and from the dust emission (46 $M_\odot$) could be due to depletion of the gas. This scenario is consistent with SMM2 being in an evolutionary stage prior to a hot molecular core.

4. Conclusions

We have carried out VLA cm and SMA mm observations toward the high-mass star-forming region ISOSS J23053+5953. From our results and discussion we want to highlight that:

1. Our observations revealed a massive CO outflow clearly associated with ISOSS J23053+5953 SMM2 which consists of a broad, low velocity component, together with a highly collimated, high velocity component.

2. Our study provides further evidence that supports the suggestion of Birkmann et al. (2007) that SMM2 is a high-mass protostar in the earliest stages of collapse.

3. The flow kinematic features observed in the moment-1 and 2 maps can be interpreted with a jet-driven model.

In summary, our observations demonstrate that ISOSS J23053+5953 SMM2 is an excellent candidate for a young high-mass object with a jet-flow system.

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