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PROTOSTELLAR FEEDBACK IN MASSIVE STAR FORMING REGIONS

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Abstract. We examine mechanical feedback mechanisms during the protostellar phase through jets and outflows. To do so, we make use of velocity-resolved [C II] observations at 158 μm taken with the SOFIA observatory. We identify [C II] emitting cavities at velocities ranging from 1-2 km s^{-1} to 15 km s^{-1} relative to the Veil shell ($v_{\rm LSR}$ = 13 km s^{-1}). The momentum and dynamical timescales of these cavities imply that the cavities in Orion were formed by fossil and active outflows from stars with luminosities ranging from 10^3 to 10^5 L$_\odot$. The momentum deposited during protostellar feedback is $\sim$1/6 of the momentum of the Veil shell deposited through winds from θ^1 Ori C. By creating cavities, the fossil outflows may already have broken the Veil shell, and outflows from less massive stars may have made the Veil shell porous.

1 Introduction

The feedback from massive stars has become one of the debated topics in modern astronomy because it is believed that stellar feedback regulates the rate of star formation, provides turbulence, and affects the evolution of galaxies (Kuiper et al., 2016; Motte et al., 2018). In this study, we divide the stellar feedback mechanisms into two subclasses, which are called protostellar feedback and main-sequence feedback. In this study, we focus on jets and outflows to play an effective role in providing feedback, or, in other words, feedback that is provided by jets and outflows in the protostellar phase. For the first time, we make a quantitative comparison of protostellar and main-sequence feedback mechanisms.

Jets and outflows from protostars play an important role as they have been proposed to solve key questions in star formation research. For example, they are used to explain the low star-formation rate (SFR) and low star formation efficiency (Krumholz, 2014; Guszejnov et al., 2021; Verliat et al., 2022), to remove angular momentum from star-forming regions (Pudritz et al., 2007; Frank et al., 2014), the observed initial mass function (Kroupa et al., 2013; Kroupa, 2014; Grudić et al., 2021), to sustain and enhance molecular cloud turbulence (Guszejnov et al., 2021; Stanke et al., 2022; Kavak et al., 2022a,b), and to produce low-density bipolar cavities altering the effects of the radiation pressure and morphology of HII regions (Kuiper et al., 2016; Kavak et al., 2022a,b).

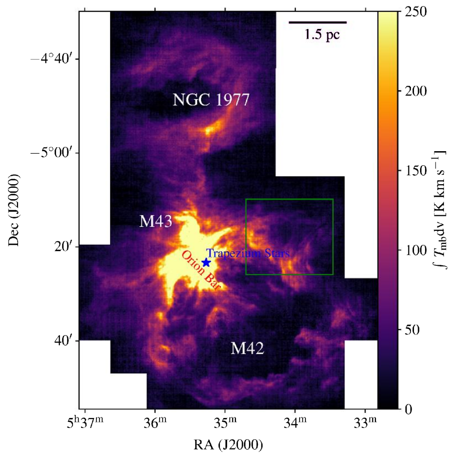

Figure 1: The integrated (between −5 and +14 km s^{-1}) intensity [C II] 158 μm map of Orion Molecular Cloud observed by upGREAT receiver on board SOFIA. The green box shows the extracted region from the map including the area of interest for this study, the protrusion (Kavak et al., 2022a).

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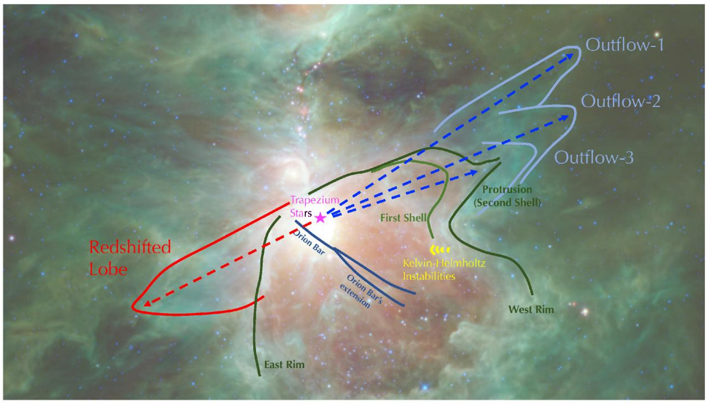

Figure 2: Protrusion and fossil bipolar outflow depicted schematically with apparent structures superimposed on the WISE image. The blue and red colors, respectively, represent the proposed blue- and red-shifted outflow lobes. Yellow structures indicate the Kelvin-Helmholtz instabilities (see Kavak et al., 2022a, for more details).

The Orion Veil is a series of layers of gas and dust shell expanding as a half spherical expanding shell at a velocity of 13 km s^{-1} (Pabst et al., 2019). We have also identify a small "half expanding shell" near the north-west rim of the bubble (see Fig. 1). Our [C II] PV diagram analysis reveals two half-expanding shells at 6.6 km s^{-1} and 11.4 km s^{-1} (Kavak et al., 2022a). The size of the protrusion (the second protrusion in Fig. 2) is 1.3 pc which is measured in the north-west direction from the Veil's rim. In addition, we find three outflow-like structures that could be associated with the Veil shell. We estimate the mass in the [C II] emitting protrusion's shell using *Herschel* dust observations and SED fitting. Using mass and velocity estimations, we calculate the momentum deposited into the first and second protrusions. Assuming that outflow momentum is conserved over the course of their lifetime, we estimate the type of protostar that is responsible for ejecting the aforementioned outflow. We find that this protrusion is related to the presence of a pre-existing cavity –carved by the powerful jet of a massive protostar– that is now overtaken by the bubble driven by the stellar wind from the main sequence 06.5 star, θ^1 Ori C (Kavak et al., 2022a). We find that the Veil bubble will first break at this position, venting its hot gas into the surrounding low-density medium. As the pressure drops, further expansion of the Veil will slow down. One might expect to find a red-shifted lobe if the protrusion is driven by a bipolar outflow. We also highlight the possible blue-shifted outflow lobes as well as the red-shifted lobe that could be ejected from the Trapezium cluster. We think that this outflow interacted with a denser region in the east of the cloud and became extinct due to this collision. However, further research is needed to verify this theory.

2 Other protrusions

We also search for protrusion-like structures that might be associated to the Veil shell in Doppler space. We employ a series of PV diagrams covering the whole set of M42 bubble [C II] observations for this. In addition to the expanding Veil shell, we discover six shock-accelerated [C II] emitting gas structures, or so-called dents, with diameters ranging from 0.3 to 1.35 pc and expansion velocities from 4 to 14 km s^{-1} (see Fig. 3). The [C II] line widths toward the dents range from 4 to 16 km s^{-1}. In addition, only the [C II] PV diagram exhibits dents; neither the ^{12}CO nor the H I 21 cm PV diagrams do. Using the momenta and timescale estimations, we get to the conclusion that less massive stars, especially B-type stars in the Orion Nebula, have an impact on the dynamics of the expanding Veil shell in addition to the O-type stars in the Trapezium cluster (see Kavak et al., 2022b, for more details).

3 Conclusions

Using the momenta estimation of the Veil shell and fossil and active outflows, we find that the momentum deposited into the Veil shell is ∼15% through protostellar feedback and ∼85% through main-sequence feedback. The fossil outflows of massive protostars influence the morphology of the future HII region and the effects of the radiation pressure. The [C II] 158 μm line observations of NGC 7538, W43, and RCW 79

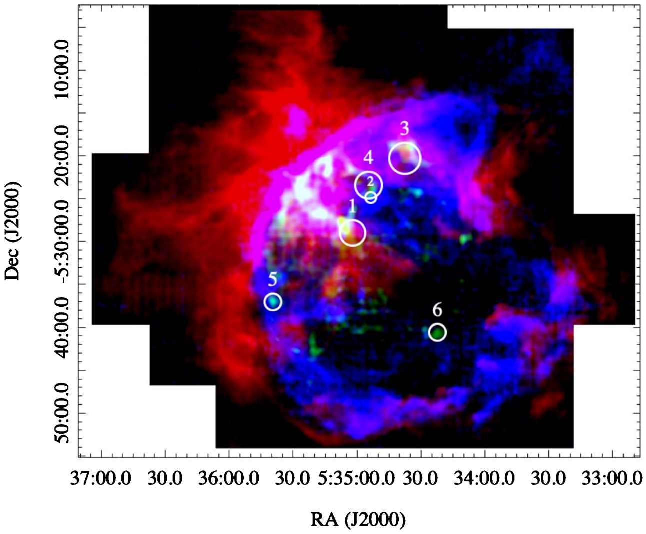

Figure 3: Three-color map of [C II] dents in the Orion Nebula (Kavak et al., 2022b). Red color represents the integrated [C II] emission from the OMC between +20 and +3 km s^{-1}. Blue represents the blue-shifted [C II] emission generated by the Veil shell moving between +3 and −3 km s^{-1}. Green represents high-velocity [C II]-emitting gas at velocities ranging from −3 to −20 km s^{-1}. The white circles indicate the position and size of the dents.

from the SOFIA FEEDBACK Legacy Survey also show that main-sequence and protostellar feedback act together in massive star-forming regions. Thus, the velocity-resolved [CII] observations from this survey will be crucial to better understanding stellar feedback mechanisms (Schneider et al., 2020).

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