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# High-velocity extended molecular outflow in the star-formation dominated luminous infrared galaxy ESO 320-G030

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## ABSTRACT

We analyze new high spatial resolution (~60 pc) ALMA CO(2–1) observations of the isolated luminous infrared galaxy ESO 320-G030 ($d$ = 48 Mpc) in combination with ancillary *HST* optical and near-IR imaging as well as VLT/SINFONI near-IR integral field spectroscopy. We detect a high-velocity (~450 km s$^{-1}$) spatially resolved (size~2.5 kpc; dynamical time ~3 Myr) massive (~$10^7$ $M_\odot$; $\dot{M}$ ~2–8 $M_\odot$ yr$^{-1}$) molecular outflow originated in the central ~250 pc. We observe a clumpy structure in the outflowing cold molecular gas with clump sizes between 60 and 150 pc and masses between $10^{5.5}$ and $10^{6.4}$ $M_\odot$. The mass of the clumps decreases with increasing distance, while the velocity is approximately constant. Therefore, both the momentum and kinetic energy of the clumps decrease outwards. In the innermost (~100 pc) part of the outflow, we measure a hot-to-cold molecular gas ratio of $7\times10^{-5}$, which is similar to that measured in other resolved molecular outflows. We do not find evidence of an ionized phase in this outflow. The nuclear IR and radio properties are compatible with strong and highly obscured star-formation ($A_k$ ~ 4.6 mag; SFR ~ 15 $M_\odot$ yr$^{-1}$). We do not find any evidence for the presence of an active galactic nucleus. We estimate that supernova explosions in the nuclear starburst ($\nu_{SN}$ ~ 0.2 yr$^{-1}$) can power the observed molecular outflow. The kinetic energy and radial momentum of the cold molecular phase of the outflow correspond to about 2% and 20%, respectively, of the supernova output. The cold molecular outflow velocity is lower than the escape velocity, so the gas will likely return to the galaxy disk. The mass loading factor is ~0.1–0.5, so the negative feedback due to this star-formation powered molecular outflow is probably limited.

**Key words.** Galaxies: ISM — Galaxies: kinematics and dynamics — Galaxies: nuclei — Galaxies: starburst — Radio lines: galaxies

— 近傍LIRGを高解像度(60pc)で観測したALMAのCO(2-1)輝線データから、outflowをする分子雲ガスclumpを発見した。
— 外側のclumpほど運動エネルギーや角運動量が小さいが、outflowの速度は一定
— そのエネルギーや角運動量はSNで説明可能
— mass loading factor (Mout/SFR)が0.1-0.5と小さく、星形成によるnegative feedbackは効いていない

## ①天体情報

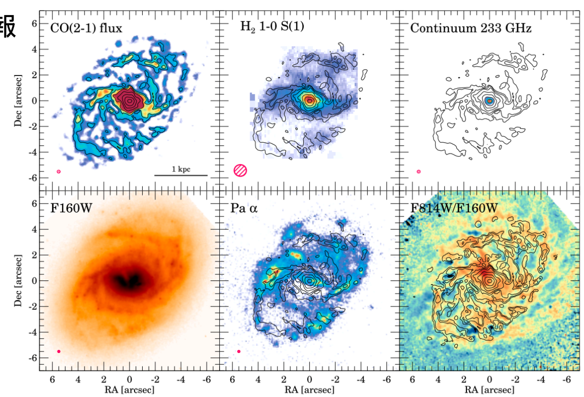


**Fig. 1.** The top row shows the ALMA $^{12}$CO(2–1), VLT/SINFONI $H_2$ 1–0 S(1) 2.12 μm, and ALMA 233 GHz continuum (rest frequency) maps of ESO 320-G030. The contours in all the images correspond to the CO(2–1) emission in logarithmic steps (1, 2, 4, 8, 16, 32, 64)×0.43 Jy km s$^{-1}$ beam$^{-1}$. The lower panels show the *HST*/NICMOS F160W and continuum subtracted Paα maps and the *HST* F814W to F160W ratio to highlight obscured regions (red colors indicate more obscured regions). In the last panel we added an extra contour level at 0.5×0.43 Jy km s$^{-1}$ beam$^{-1}$. The red hatched ellipses indicate the beam size of each image. For the ALMA CO(2–1) and the 233 GHz continuum images, the beam size is 0.″25×0.″23, PA 89°. For the SINFONI $H_2$ 1–0 S(1) image, the beam FWHM is 0.″6, and for the *HST*/NICMOS data, the beam is ~0.″15.

ESO320-G030, d=48Mpc (z=0.010781)
log (L_IR/L_sun) = 11.35 → total SFR = 28 M_sun
AGNではなく、star-forming銀河

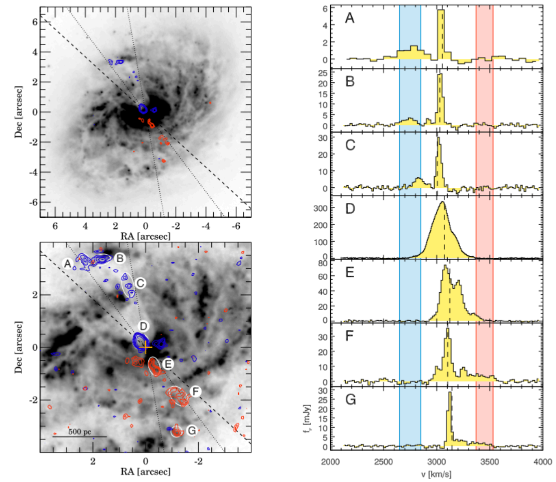


**Fig. 6.** The left panels show the CO(2–1) integrated emission between 2650 and 2850 km s$^{-1}$ in blue contours and between 3370 and 3530 km s$^{-1}$ in red contours. The contours correspond to 3, 4, 5, 6, 8, and 12σ levels in their respective bands (the 3σ contour level is not plotted in the top left panel for clarity). The background of the top left panel is the *HST*/ACS F814W image which shows the internal spiral arms. The background of the bottom left panel is the *HST*/ACS FR656N image to maximize the contrast of the dust lanes. The dashed line indicates the minor kinematic axis and the dotted lines indicate the approximate opening angle of the outflowing gas. The orange cross marks the position of the 233 GHz continuum peak. The right panels show the CO(2–1) spectra of the regions marked in the bottom left panel. The blue and red shaded areas indicate the velocity ranges used to construct the blue and red contours, respectively. The vertical dashed line corresponds to the velocity derived in Section 4 assuming a rotating disk model. To increase the signal-to-noise ratio, we binned the spectra in channels of 60, 20, 15, 5, 15, 20, and 20 km s$^{-1}$ from top to bottom.

## ②CO分子ガス速度場

— モデルfitした回転曲線から200km/sもoffsetした速度成分が、銀河中心に対して対照的に分布

— これは密度波理論から予測されるガス速度や、中心部に見られるsub-diskの速度(~70km/s)よりもずっと大きい

— 各分子雲ガスの、回転曲線からの速度のoffsetは370-540km/sで、中心からの距離には依存しない

**Table 1.** Properties of the outflow regions

あくまでlower limit (→ log $M_{mol}$)

| Region | $d/\sin i^a$ (pc) | $v/\cos i^b$ (km s$^{-1}$) | $\sigma^c$ (km s$^{-1}$) | $f$(CO(2–1))$^d$ (mJy km s$^{-1}$) | log $M_{mol}{}^e$ ($M_\odot$) | log $E_{out}{}^f$ (erg) | $t_{dyn}{}^g$ (Myr) | FWHM$^h$ (pc) |
|---|---|---|---|---|---|---|---|---|
| A | 1320 | –460±23 | 70±10 | 250±10 | 5.5 | 53.8 | 2.8±0.2 | 70±20 |
| B | 1210 | –510±16 | 50±7 | 374±15 | 5.7 | 54.1 | 2.3±0.1 | 80±20 |
| C | 800 | –367±9 | 33±4 | 474±13 | 5.8 | 53.9 | 2.1±0.1 | 70–110 |
| D | 90 | [–530,–320]* | ··· | 1940±30 | 6.4 | 54.6 | 0.2±0.1 | 90±10 |
| E | –250 | 370±11 | 42±5 | 1044±15 | 6.1 | 54.2 | 0.7±0.1 | 150±30 |
| F | –730 | [330, 750]* | ··· | 920±40 | 6.1 | 54.5 | 1.4±0.3 | ~100 |
| G | –1100 | [390, 690]* | ··· | 210±30 | 5.5 | 53.7 | 2.4±0.4 | 60±20 |

clumpのK.E.とmomentumのrate (total K.E. or momentをdynamical timeで割ったもの) はそれぞれ4×10$^{48}$erg/s/yr, 10$^3$M_sun km/sで、SNのレートが0.2/yrとしたときの生成率の2-20%で、SN起源として説明可能。
ちなみに、SNの発生率は4.85GHzの光度(Colina+93)やSFRから直接(Kroupa01)求められる。

outflow clumpの分子雲ガス質量はtotalで6.8M_sun (ただしlower limit)
dynamical time ~ 3Gyrを仮定すると、$\dot{M}_{out} = 1.7 M_\odot$/yrより、mass loading factor ~ 0.1
→この銀河はoutflowした分子雲ガスをリサイクルしている
この銀河の周りをゆっくりと回転するように中性分子雲ガスが分布している(Cazzoli+14)ことと無矛盾

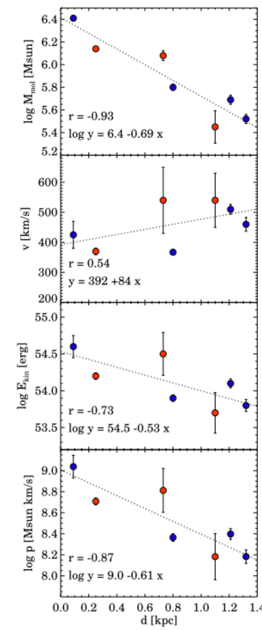


**Fig. 7.** Logarithm of the molecular mass (first), velocity (second), kinetic energy (third), and momentum (fourth) of the outflowing clumps as a function of the deprojected distance from the nucleus. Blue and red points are blueshifted and redshifted clumps, respectively. The dotted line is the best fit. The parameters of the best fit and the Pearson correlation coefficients are indicated in each panel. The error bars correspond to the statistical uncertainties.