Jet acceleration of the fast molecular outflows in the Seyfert galaxy IC 5063

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Massive outflows driven by active galactic nuclei are widely recognized to have a key role in the evolution of galaxies1–4, by heating the ambient gas, expelling it from the nuclear regions, and thereby affecting the star-formation histories of the galaxy bulges. It has been proposed that the powerful jets of relativistic particles (such as electrons) launched by some active nuclei can both accelerate5–7 and heat8 the molecular gas, which often dominates the mass budgets of the outflows5,9. Clear evidence for this mechanism, in the form of detailed associations between the molecular gas kinematics and features in the radio-emitting jets, has however been lacking. Here we report that the warm molecular hydrogen gas in the western radio lobe of the Seyfert galaxy IC 5063 is moving at high velocities—up to about 600 kilometres per second—relative to the galaxy disk. This suggests that the molecules have been accelerated by fast shocks driven into the interstellar medium by the expanding radio jets. These results demonstrate the general feasibility of accelerating molecular outflows in fast shocks driven by active nuclei.

IC 5063 (redshift z = 0.0113) is a massive early-type galaxy (with stellar mass $M_* \approx 10^{11} M_\odot$, where $M_\odot$ is the mass of the Sun), which hosts both a type II Seyfert nucleus and a powerful double-lobed radio source ($P_{1.4 \text{GHz}} = 3 \times 10^{25} \text{ W Hz}^{-1}$). The first signs of outflows driven by the active nucleus in this object were provided by the detection of extended blue wings to the HI 21-cm absorption feature and optical [O iii] emission lines at the site of the radio lobe 2.0 arcsec (0.45 kpc) to the west of its nucleus10–12. Subsequently, a blue wing was also detected in the CO(2–1) emission line profile of the integrated emission from the galaxy, providing evidence for molecular outflows5. However, the low spatial resolution of the millimetre-wavelength CO observations of this and similar objects5–7 prevented a direct link being established between the putative molecular outflows and the relativistic jets and lobes associated with the active nucleus.

To overcome the resolution problem we have obtained deep, near-infrared long-slit spectroscopic observations of IC 5063, taken with the

Figure 1 | Signs of extreme kinematic disturbance in the western radio lobe of IC 5063. The central panel shows a greyscale representation of our long-slit, near-infrared (K-band) spectrum of IC 5063, covering a wavelength range centred on the H$_2$ 1−0 S(1) line. For comparison, a scaled version of the 1.4-GHz radio map of the source is presented on the right. The velocity profiles derived from spectra extracted from three spatial locations across the galaxy are presented on the left, where the solid blue lines represent the H$_2$ 1−0 S(1) feature, and the dotted red lines represent the Brackett-gamma feature.
slit aligned along the axis of the extended radio lobes and jets. The observations were made in good seeing conditions (full width at half-maximum, FWHM = 0.6 arcsec) and cover the H$_2$ 1–0 S(1) $\lambda = 2.128$ $\mu$m (change in vibrational quantum number $v = 1 \rightarrow 0$; change in rotational quantum number $J = 3 \rightarrow 1$) and H$_2$ 2–1 S(2) $\lambda = 2.154$ $\mu$m ($v = 2 \rightarrow 1$, $J = 4 \rightarrow 2$) rotational-vibrational lines of molecular hydrogen, as well as the Brackett-gamma $\lambda = 2.166$ $\mu$m line emitted by the warm ionized hydrogen gas at the same spatial locations in the galaxy. In Fig. 1 we show a greyscale representation of the long-slit spectrum, as well as line profiles extracted for three key regions in the galaxy. Although extended molecular hydrogen emission is detected along the full 14–arcsec length of the spectroscopic slit, the surface brightness of the emission is particularly high in the regions encompassed by the lobes of the radio source (± 2 arcsec on either side of the nucleus), consistent with previous Hubble Space Telescope imaging observations$^{13}$. Most strikingly, the kinematics of the molecular gas are highly disturbed at the position of the western radio lobe, where the H$_2$ 1–0 S(1) $\lambda = 2.128$ $\mu$m line shows a broad, complex profile with a full width at zero intensity of $\text{FWZI} \approx 1,200$ km s$^{-1}$; the H$_2$ emission line profile at this location is clearly broader than that of the nucleus or of the eastern radio lobe.

In Fig. 2 we show the results obtained by fitting single Gaussian profiles to the H$_2$ 1–0 S(1) $\lambda = 2.128$ $\mu$m emission line profile at several spatial locations along the slit. From this it is clear that both the H$_2$ surface brightness and the linewidth peak at the position of the western radio lobe. Moreover, while the molecular gas at large radius follows the rotation curve of the extended disk of the galaxy$^{10,12}$, distortions in the radial velocity curve are apparent at the positions of the eastern and western radio lobes. Clearly, the highly disturbed emission line kinematics measured in the radio lobes cannot be explained by the normal gravitational motions of the gas in the galaxy. Therefore, these results provide clear and unambiguous evidence that the molecular gas, like the neutral H I gas$^{10,11}$, has been accelerated as a result of the interactions between the expanding radio lobes and the interstellar medium in the galaxy disk.

In terms of the comparison with the outflows detected in other phases of the interstellar medium (see Fig. 3), the H$_2$ line profile for the western lobe encompasses the full range of blueshifted absorption lines measured in the broad, H I 21-cm absorption line$^{10,11}$, but has a strong, redshifted wing that is not present in the H I feature. The latter difference can be explained by the fact that, whereas the H I absorption line samples only the gas in the foreground of the radio lobe, the H$_2$ emission line samples the outflowing gas moving towards and away from the observer, on the near- and far-side of the lobe, respectively. In this sense the H$_2$ velocity profile is similar to that of warm ionized gas, as represented by the near-infrared Brackett-gamma line, whose kinematics closely follow those of the high ionization optical emission lines (for example, [O III] $\lambda = 5,007$ Å (ref. 12). However, although the Brackett-gamma velocity profiles cover a similar velocity range to those of the H$_2$ line, they are different in detail (see Figs 1 and 3).

The detection of a weak H$_2$ 2–1 S(2) $\lambda = 2.154$ $\mu$m emission line in the western lobe allows us to estimate the temperature of the molecular gas in the outflow region, since this feature has a higher excitation energy than the H$_2$ 1–0 S(1) line. The ratio between the two H$_2$ lines (H$_2$ 2–1 S(2)/H$_2$ 1–0 S(1) = 0.027 ± 0.03) is consistent with a gas temperature of 1,913$^{+32}_{-68}$ K, assuming that the molecular gas is thermalized. Using this temperature and the spatially integrated H$_2$ 1–0 S(1) luminosity ($L_{H_2} = (1.7 \pm 0.1) \times 10^{22}$ W), we estimate$^{4}$ a molecular hydrogen mass of $M_{H_2} = (8.2 \pm 1.2) \times 10^5$ solar masses for the western outflow region, which is several orders of magnitude lower than the H$_2$ mass estimated from the blueshifted CO(2–1) emission feature ($2.25 \times 10^5 < M_{H_2} < 1.29 \times 10^8$ solar masses)$^5$.

Our observations are consistent with a model in which the relativistic jets are expanding through the clumpy interstellar medium in the disk of the galaxy, driving fast shocks into dense molecular clouds embedded in a lower-density medium$^{15,16}$. As the molecular gas enters the shocks it is accelerated and simultaneously heated to high temperatures ($T > 10^4$ K), ionizing the gas, and dissociating the molecules. The post-shock gas then cools to around $10^4$ K, emitting emission lines associated with warm ionized gas (for example, Brackett-gamma) as it does so. Further cooling of the gas below $10^4$ K leads to the formation of molecular hydrogen and other molecules, and the near-infrared rotational-vibrational lines of H$_2$ are emitted efficiently as the warm gas cools through the temperature range 5,000–1,000 K; at this stage there is also sufficient neutral hydrogen to allow strong absorption in the H I 21-cm line. Eventually, the molecular line emission cools the gas to low temperatures (<100 K), where it is detected through the millimetre-wavelength CO molecular lines. In this scenario, the substantial difference between the H$_2$ masses estimated from the near-infrared rotational-vibrational H$_2$ lines and the millimetre-wavelength CO lines is explained by the fact that the near-infrared H$_2$ lines represent a transitory phase in the warm, post-shock.

![Figure 2](image_url)
Although this mechanism has not been entirely ruled out, the alternative slow entrainment mechanism, when active, should be detectable via the close alignments between the radio and optical/ultraviolet structures in high-redshift radio galaxies. However, it has proved challenging to find definitive evidence for this mechanism, given the presence of continuum components related to the active galactic nuclei, such as scattered quasar light and nebular continuum, which are likely to be particularly strong in powerful, high-redshift objects. At present, the best observational evidence for jet-induced star formation is provided by detailed observations of a few well-resolved radio galaxies of relatively low power in the local Universe. Clearly, the detection of molecular hydrogen outflows in the western radio lobe of IC 5063 lends further credibility to this mechanism.

METHODS SUMMARY

The near-infrared observations of IC 5063 were taken using the medium-resolution mode of the Infrared Spectrometer and Array Camera (ISAAC) on the European Southern Observatory’s Very Large Telescope, with the spectroscopic slit aligned along the radio axis (PA 295°). A standard ABA nod pattern was employed, with a 20-arcsec nod throw, 3-arcsec dither box, and 300-s exposures at each position. Four repeats of the basic nod pattern resulted in a total exposure time of 4800 s, and sky subtraction was affected by subtracting the co-aligned/co-added A and B spectra. The data were then wavelength-calibrated using the bright night-sky lines detected in the spectra, and flux-calibrated using observations of the B3V star HIP 17135 taken at a similar air mass. Use of a 1.0-arcsec slit resulted in a spectral resolution of R = 3000 (100 km s⁻¹), and the data cover a useful wavelength range of 2.104–2.230 μm, with a spatial scale of 0.146 arcsec per pixel.

Radial velocities, line widths, and line fluxes were determined using the STARLINK DIPSO package (http://www.starlink.ac.uk/docs/sun50.htm#sun50.html) to fit single Gaussian profiles to the emission lines. All the velocities are measured relative to the rest frame of the host galaxy, as determined using the wavelength centroids of the H₂ and Bracket-gamma emission lines measured in the nucleus (z = 0.01131 ± 0.00004), and the line widths have been corrected for the instrumental profile.

At the redshift of IC 5063, 1.0 arcsec corresponds to 0.224 kpc for our assumed cosmology (H₀ = 70 km s⁻¹ Mpc⁻¹, z₀ = 0.3, Ω = 0.7). Using this cosmology, the stellar mass for IC 5063 quoted in the main text was estimated from the 36-arcsec aperture K-band magnitude, assuming a K-band mass-to-light ratio of (MJ/K) = 0.9.

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