IC 630: Piercing the Veil of the Nuclear Gas

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Abstract

IC 630 is a nearby early-type galaxy with a mass of $6 \times 10^{10} M_\odot$ with an intense burst of recent (6 Myr) star formation (SF). It shows strong nebular emission lines, with radio and X-ray emission, which classifies it as an active galactic nucleus (AGN). With VLT-SINFONI and Gemini North-NIFS adaptive optics observations (plus supplementary ANU 2.3 m WiFeS optical IFU observations), the excitation diagnostics of the nebular emission species show no sign of standard AGN engine excitation; the stellar velocity dispersion also indicates that a supermassive black hole (if one is present) is small ($M_\bullet = 2.25 \times 10^5 M_\odot$). The luminosity at all wavelengths is consistent with SF at a rate of about 1–2 $M_\odot$ yr$^{-1}$. We measure gas outflows driven by SF at a rate of 0.18 $M_\odot$ yr$^{-1}$ in a face-on truncated cone geometry. We also observe a nuclear cluster or disk and other clusters. Photoionization from young, hot stars is the main excitation mechanism for [Fe II] and hydrogen, whereas shocks are responsible for the H2 excitation. Our observations are broadly comparable with simulations where a Toomre-unstable, self-gravitating gas disk triggers a burst of SF, peaking after about 30 Myr and possibly cycling with a period of about 200 Myr.

Key words: galaxies: active – galaxies: individual (IC 630) – galaxies: ISM – galaxies: nuclei – galaxies: starburst – galaxies: star formation

1. Introduction

1.1. Active Galactic Nuclei and Star Formation

Active galactic nuclei (AGNs) and their host galaxies have a close association, with the mass of the supermassive black hole (SMBH) that ultimately powers the activity being correlated with several galaxy properties: stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000), galactic bulge mass (Kormendy 1993), K-band luminosity (Kormendy & Richstone 1995; Graham & Scott 2013), and the light profile (Sérsic index; Graham et al. 2001). As the “sphere of influence” of the SMBH is tiny compared to the scale of the galaxy, feedback mechanisms must link the mutual mass growths together. These can be either negative, where AGN energetics suppress star formation (SF; Puchwein & Springel 2013), or positive, enhancing SF (e.g., van Breugel & Dey 1993; Mirabel et al. 1999; Mould et al. 2000). Nearby galaxies hint that these two processes are not mutually exclusive, but are closely coupled (Floyd et al. 2013; Rosario et al. 2010). At high AGN powers, there is enough energy transfer to the interstellar medium (ISM) to suppress SF. However, for most of the time, AGNs are in a low-power mode; recent observations (Villar-Martín et al. 2016) suggest that even luminous AGNs have low to modest outflows, not enough to suppress SF. Scenarios can be suggested where low-power outflows, radio jets, or gravitational instabilities compress the ISM to enhance SF. Watabe et al. (2007) demonstrate a positive correlation between AGNs and nuclear starburst luminosities; Zubovas et al. (2013) predict this from numerical simulations (see Watabe et al. 2007, for an overview). Recent observations of the Phoenix cluster with ALMA (Russell et al. 2016) show that, even at very high powers, production of cold gas is stimulated by radio bubbles to provide SF fuel.

Three-dimensional adaptive mesh refinement (AMR) hydrodynamic simulation models can resolve the accretion disk, dusty torus, broad- and narrow-line regions, and large-scale inflows and outflows in a range of timescales and space scales (Schartmann et al. 2009; Wada et al. 2009). Observationally, with current instrumentation, we can resolve at sub-10 pc scales those objects with a distance of less than 100 Mpc.

1.2. Our Program

Our program is to study the nuclear activity of nearby early-type galaxies with radio emission for AGNs and SF activity, to elucidate the details of the feedback mechanisms. We map the material flows through 2D velocity structures and study the gas excitation to determine the relative contributions of the activity modes. This mapping is at the smallest possible scale, close to the central engine. Our sample is based on the Brown et al. (2011) early-type galaxy radio catalog, which demonstrated the likelihood that all massive early-type galaxies harbor an AGN and/or have undergone recent SF. Using this catalog, Mould et al. (2012) conducted long-slit spectroscopic observations and found that about 20% of objects showed IR emission lines; these have greater radio power for a given galaxy mass than those without such lines. We select elliptical and lenticular galaxies, as the fueling and stellar populations are likely to be simpler than spirals, stored gas is smaller, and there is a minimum of nuclear obscuration.

We also select objects with a distance <80 Mpc; resolving 2D gas flow velocity structures requires integral field spectroscopes/units (IFS/IFU), and this distance limit enables adaptive optics (AO) corrected IFU observations at sub-10 pc resolution. AO performs best in the infrared, which also has the advantage of penetrating obscuring gas and dust to directly observe the nuclear region. Currently, there are three instruments that meet the combined requirements of a telescope in the 8–10 m class, adaptive optics, and a near-infrared IFU: these are SINFONI on VLT (Eisenhauer et al. 2003), NIFS on Gemini North (McGregor et al. 2003), and OSIRIS on Keck I (Larkin et al. 2006).
This paper is the second on the Mould et al. (2012) galaxies. The first was on NGC 2110 (Durré & Mould 2014), which showed young, massive star clusters embedded in a disk of shocked gas from stellar winds that feed the black hole; the SF rate is $0.3 \, M_\odot \, yr^{-1}$, easily sufficient to produce the clusters on a million-year timescale. The gas kinematics produced an estimate for the enclosed central mass of $(3.2-4.2) \times 10^8 \, M_\odot$.

Other work has concentrated on “classical” Seyferts, which normally reside in spirals. Riffel et al. (2015) summarize the work of the AGNIFS group at the Universidade Federal de Santa Maria and the Universidade Federal do Rio Grande do Sul, Brazil, on 10 Seyfert AGNs; they find that for low-ionization nuclear emission-line regions (LINERs) and low-power Seyferts, gas in different phases has distinct distributions and kinematics, with ionized outflow rates in the range of $10^{-2}$ to $10 \, M_\odot \, yr^{-1}$ (in ionized cones or compact structures) and $H_2$ inflow rates of $10^{-3}$ to $10 \, M_\odot \, yr^{-1}$. The stellar kinematics of Seyfert galaxies reveals cold nuclear structures composed of young stars, usually associated with a significant gas reservoir. Hicks et al. (2013) and Davies et al. (2014), in their comparison of five active and five quiescent galaxies, reach the same conclusions, further finding that the quiescent galaxies have chaotic dust morphologies and counter-rotating molecular gas.

Davies et al. (2007b) observe moderately recent (10–300 Myr) starbursts around all nine of the AGNs in their heterogeneous sample, deducing episodic periods of SF. They posit a 50–100 Myr delay between SF and AGN activity onsets, concluding that OB stars and supernovae (SNe) produce winds that have too high velocities to feed the AGN, but that evolved AGB stellar winds with slow velocities can be accreted efficiently onto the SMBH.

This paper investigates the link between AGN activity and SF at small scales. We combine the near-IR observations with supplementary optical IFU observations. This paper uses Vega system magnitudes and the standard cosmology of $H_0 = 73 \, km \, s^{-1} \, Mpc^{-1}$, $\Omega_{\text{Matter}} = 0.27$, and $\Omega_{\text{Vacuum}} = 0.73$.

2. IC 630 as a Starburst

IC 630 shows the second-strongest IR emission line flux in the Mould et al. (2012) spectroscopic observation program (after the well-studied Seyfert 1 galaxy UGC 3426/Mrk 3).

IC 630’s basic details are from the NASA/IPAC Extragalactic Database (NED) unless otherwise noted. IC 630 (Mrk 1259) has a type of S0 pec (morphological type $-2$) from the RC3 catalog (de Vaucouleurs et al. 1991) with a redshift of 0.007277. Using the Virgo+GA+Shapley Hubble flow model, this gives a distance of $33.3 \pm 2.3 \, Mpc$, with a distance modulus of $32.6 \, mag$ (a flux-to-luminosity ratio of $1.3 \times 10^{53}$ in cgs units, i.e., erg cm$^{-2}$ s$^{-1}$ to erg s$^{-1}$ at the distance of IC 630). It has starburst-type activity (Balzano 1983), rather than the classical AGN-type high-excitation emission lines of Seyfert galaxies; in fact, it is classified as a “Wolf-Rayet” galaxy with a superwind, similar to M82 (Ohyama et al. 1997), with a high ratio of W-R to O-type stars ($\sim 9\%$). The outflow is seen almost face-on, with the estimated velocity of $\sim 710 \, km \, s^{-1}$. Strong optical emission lines of hydrogen, [O III], and [N II] are seen, as well as N III, N v, He I, and He II.

To illustrate global morphology and the relevant scales, Figure 1 shows images for this object: the optical from the Pan-STARRS $g$-band image, the infrared $H$-band image from the 2MASS image cutout facility, the H-band near-infrared from the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006), and the radio at 1.4 GHz from the VLA FIRST survey (Becker et al. 1995) image cutout facility. The IR image is somewhat confused by the diffracted light from the nearby star HD 92200, which has been masked out. The scale and orientation are the same in all images as shown on the optical image. The infrared image shows a featureless spheroid with a published (NED) ellipticity of about 0.5 at a position angle (PA) of about 60$^\circ$. In the Pan-STARRS $g$ optical image (Figure 1), the nucleus is off-center with respect to the disk and shows dust lanes crossing SW to NE across the nucleus, with a suggestion of a shell structure (most prominent in the NE quadrant). The radio image has a hint of a lobe toward the NW.

An estimate of the galaxy mass was calculated from the Spitzer Heritage Archive 3.6 $\mu$m and 2MASS $H$-band images. This yields $\sim 5.1 \times 10^{10} \, M_\odot$ (assuming a mass-to-light ratio of 0.8 at 3.6 $\mu$m) and $\sim 6.4 \times 10^{10} \, M_\odot$ from the 2MASS image (assuming an $M/L$ of 1 at $H$).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Left panel: optical image (Pan-STARRS $g$). Middle panel: infrared image (2MASS $H$). Right panel: radio (VLA FIRST 1.4 GHz) image. The optical and IR units are magnitude per square arcsec. The contoured radio flux units are mJy; the circle in the bottom left of the plot is the beam size. The optical image shows the FOV ($25^\prime\times 38^\prime$) for the optical WiFeS IFU as a rectangle (the regularly spaced dots are an image artifact). The IR image also shows the FOV for the infrared IFU observations ($3.3 \times 3.3$) as a small white square. The image sizes are $60^\prime$ x $60^\prime$, equivalent to $\sim 10$ kpc.}
\end{figure}

4. http://ned.ipac.caltech.edu/
5. https://archive.stsci.edu/
6. http://third.ucolq.co.uk/cgi-bin/fromcutout
To confirm the starburst characterization, the spectral energy distribution (SED) was compiled from existing data sources (Table 1), plotted in Figure 2. This confirms the type, with the major peak at around 100 μm (∼30 K) being from dust heated by SF. For comparison, the SED of the well-known starburst galaxy Arp 220 is also plotted, showing very similar features. The SED was also fitted using the magphys package with the HIGHZ extension to fit the Planck observations (da Cunha et al. 2008, 2015); the fit estimates the galaxy mass at \(\sim 1.5 \times 10^{10} M_\odot\) (somewhat lower than the mass estimate from the near-IR photometry) and a star formation rate (SFR) of \(\sim 1.1 M_\odot \text{yr}^{-1}\), in line with the values in Table 2, which presents derived SFRs from various flux indicators. It is noted that the radio flux is about a factor of 4 above the fit; this could be due to the uncertainties associated with the fit, which uses a prescription based on the far-IR and radio correlation (E. da Cunha, private communication) or from a highly obscured AGN. Nuclear starbursts are usually the result of galaxy interactions (Bournaud 2011), and the optical image shows a disturbed morphology. An examination of images from various surveys around IC 630 does not reveal any candidate interacting galaxy, so we suggest that the starburst is generated by a minor merger.

### 3. Observations and Data Reduction

#### 3.1. Observations

Our infrared observations were taken with NIFS on Gemini North in queue service observing mode and SINFONI on VLT-U4 (Yepun) in classical/visitor observing mode. Observations were carried out using adaptive optics with laser guide stars, as per Table 3.

Each data set consists of two 300 s observations, combined with a sky frame of 300 s, in the observing mode “Object-Sky-Object.” The NIFS observations used simple nodding to the sky position, which was 30″ in both R.A. and decl.; for SINFONI the offset was 30″ in decl., plus a 0″05 jittering procedure. Ancillary calibration observations were carried out on each night. For NIFS, these consist of arc, flat field, dark, and Ronchi slit-mask (for spatial calibrations). For SINFONI, these are dark current, flat field, linearity and distortion flat fields, and arc and arc distortion frames. These are combined with static calibration data: line reference table, filter-dependent setup data, bad pixel map, and atmospheric refraction reference data.

Our optical observations were taken on using the WiFeS instrument (Dopita et al. 2007, 2010) on the Australian National University’s 2.3 m telescope at Siding Spring Observatory. The WiFeS IFU has a 23′′ × 38′′ field of view (FOV) and 1″ × 1″ spaxels. The B3000 (5500–5800 Å) and R3000 (5300–9000 Å) gratings were used along with the RT560 dichroic. The instrument was used in “Classical Equal” observation mode, with an average seeing of 2″.

#### 3.2. Data Reduction

For the NIFS observation sets, the standard Gemini IRAF recipes were followed. This consists of creating baseline calibration files and then reducing the object and telluric
observations using these calibrations. Each on-target frame is subtracted by the associated sky frame, flat-fielded, bad pixel corrected, and transformed from a 2D image to a 3D cube using the spatial and spectral calibrations. The resulting data cubes are spatially resampled to 50 × 50 mas pixels. The resulting six data cubes for each filter set were manually registered by collapsing the cube along the spectral axis, measuring the centroid of the nucleus, recentering each data cube, and collapsing the cube along the spectral axis, measuring the centroid of the nucleus, recentering each data cube, and averaging-combining them.

For the SINFONI observation sets, we used the recommendations from the ESO SINFONI data reduction cookbook and the gasgano\textsuperscript{8} software pipeline (version 2.4.8). Bad read lines were cleaned from the raw frames using the routine provided in the cookbook. Calibration frames were reduced to produce non-linearity bad pixel maps, dark and flat fields, distortion maps, and wavelength calibrations. Sky frames are subtracted from object frames, corrected for flat field and dead/hot pixels, interpolated to linear wavelength and spatial scales, and resampled to a wavelength-calibrated cube, which also has pixels of 50 × 50 mas size. The reduced object cubes are mosaicked and combined to produce a single data cube.

The spectra were not reduced to the rest frame, as the target lines have good signal-to-noise ratio (S/N), making identification unproblematic. The three final infrared data cubes (one each for \( J, H, \) and \( K \) band) conveniently all have the same native spatial sampling (0\textquoteright\textquoteright 0.05); these were resized so that all were 66 × 66 pixels (3.3 × 3.3\textquoteright\textquoteright), and centered to the brightest pixel (the nuclear core), with an FOV of ∼540 × 540 pc at the galaxy. With this resolution, the plate scale is 8.2 pc pixel\textsuperscript{-1}.

The optical WiFeS data were reduced in the standard manner using the PyWiFeS reduction pipeline of Childress et al. (2013), with flat-fielding, aperture and wavelength calibration, and flux calibration from the standard star. The spatial pixel scale of 1\textquoteright\textquoteright is equivalent to 164 pc; the whole FOV is 4.1 × 6.6 kpc. The data reduction produces a data cube for each of the blue and red filters. These were attached together in the wavelength axis, and the red cube was resampled to the same dispersion as the blue cube (0.0774 nm pixel\textsuperscript{-1}). The spectrum at each pixel showed considerable sky background, including skyline emission, especially redward of 7200 Å; this background was removed by subtracting the median spectrum of purely sky pixels.

\footnote{http://www.eso.org/sci/software/gasgano.html}

### 3.3. Telluric Correction, Flux Calibration, and PSF Estimation

The telluric and flux calibration data reduction was carried out for each infrared instrument in the same manner. The standard stars (listed in Table 3) were used for both telluric correction and flux calibration. The telluric spectrum can be modeled by a blackbody curve for the appropriate temperature plus simple Gaussian fits to remove the hydrogen and helium lines. The best blackbody temperature fit to the telluric star’s spectrum observed in the infrared is somewhat higher than the stellar type’s nominal optical temperature (by about a factor of 1.3); the hydrogen opacity is lower at infrared wavelengths, so we observe a lower (and therefore hotter) layer in the stellar atmosphere. This was confirmed by checking the stellar atmospheric model templates from Castelli & Kurucz (2003) (available from the Space Telescope Science Institute\textsuperscript{10}), using the ckip00 set of models for standard main-sequence stars of solar metallicity.

To extract the spectrum of the star, the aperture to be used must be carefully determined. With multiple elements in the optical train, the IFU image shows significant scattered light over more than 1 s radius. The aperture is set manually from the cube median image, using logarithmic scaling. A region outside this aperture was chosen to set the background level offset. For telluric correction, a blackbody curve of the appropriate temperature is removed and the absorption lines interpolated over. This was then normalized and divided into each spectral element of the science data cube.

Flux calibration was done by reference to the spectrum and the \( J, H, \) or \( K \) magnitude from the 2MASS catalog. The magnitude is converted to flux using the Gemini Observatory calculator “Conversion from magnitudes to flux, or vice-versa”\textsuperscript{10} (Cohen et al. 1992). The count calibration is done by averaging over a 10 nm range around the filter effective wavelengths (\( J: 1235 \text{ nm}; H: 1662 \text{ nm}; K: 2159 \text{ nm} \)) to get the counts, and the flux calibration is computed (in erg cm\textsuperscript{-2} s\textsuperscript{-1} coun\textsuperscript{-1}). These effective wavelengths will be used subsequently for surface brightness maps, along with the Johnson \( V \) effective wavelength (550 nm).

It is well known that the flux calibration for IFU instruments can produce uncertainties of the order of 10%; our observations are also from two different instruments at three separate dates.

\footnote{ftp://ftp.stsci.edu/cdfs/grid/ckp04models/}

\footnote{http://www.gemini.edu/sciops/instruments/midir-resources/imaging-calibrations/fluxmagnitude-conversion}

\begin{table}[h]
\centering
\caption{Star Formation Rates for Various Indicators}
\begin{tabular}{|l|l|c|c|c|c|c|}
\hline
Passband & Instrument & \( \lambda/\nu/\text{eV} \) & Ref. & Flux & Units & Luminosity & Units & SFR (M\(_\odot\) yr\textsuperscript{-1}) \\
\hline
Radio & MWA GLEAM Survey & 150 MHz & 3 & 0.22 Jy & 2.1 × 10\textsuperscript{22} W Hz\textsuperscript{-1} & 2.8 & & \\
Radio & VLA & 1.4 GHz & 2 & 0.067 Jy & 8.9 × 10\textsuperscript{21} W Hz\textsuperscript{-1} & 3.6 & & \\
Mid-IR & WISE W4 & 22.8 \( \mu \text{m} \) & 1 & 3.9 Jy & 6.8 × 10\textsuperscript{33} erg s\textsuperscript{-1} & 10.3 & & \\
Mid-IR & WISE W3 & 11.6 \( \mu \text{m} \) & 1 & 0.7 Jy & 2.4 × 10\textsuperscript{33} erg s\textsuperscript{-1} & 5.8 & & \\
H\( \alpha \) & Oyakama NCS & 6562.8 Å & 5 & 2.77 × 10\textsuperscript{-12} erg cm\textsuperscript{-2} s\textsuperscript{-1} & 3.7 × 10\textsuperscript{41} erg s\textsuperscript{-1} & 2.0 & & \\
Far-IR & GALEX & 1538.5 Å & 4 & 2.20 × 10\textsuperscript{-3} Jy & 5.8 × 10\textsuperscript{22} erg s\textsuperscript{-1} & 2.9 & & \\
X-ray & ASCA & 0.7–2 keV & 6 & 3.20 × 10\textsuperscript{-13} erg cm\textsuperscript{-2} s\textsuperscript{-1} & 3.1 × 10\textsuperscript{40} erg s\textsuperscript{-1} & 6.8\textsuperscript{1} & & \\
X-ray & ASCA & 0.7–10 keV & 6 & 3.90 × 10\textsuperscript{-13} erg cm\textsuperscript{-2} s\textsuperscript{-1} & 5.2 × 10\textsuperscript{40} erg s\textsuperscript{-1} & 13.0\textsuperscript{1} & & \\
\hline
\end{tabular}
\end{table}

\textbf{Note.} SFR indicators are from M. J. I. Brown et al. (2017, in preparation), except for those marked with a dagger, which are from Ranalli et al. (2003).

\textbf{References.} (1) IRSA AllWISE Catalog (Wright et al. 2010); (2) NAO VLA Sky Survey (Condon et al. 1998); (3) MWA GLEAM Survey (Hurley-Walker et al. 2017); (4) GALEX data archive; (5) Ohyama et al. 1997; (6) Ueda et al. 2005.
We therefore cross-checked the calibration against the long-slit infrared observations from Mould et al. (2012). Using the longslit function in the data viewer and analysis package Q Fits View (Ott 2016), we extracted the spectra of a pseudo-long slits from each data cube with the same width and PA (1′ = 20 pixels, PA = 208°) and compared it with the Mould et al. (2012) long-slit observations. These were plotted together as shown in Figure 3; the three IFU observations are smoothly continuous, demonstrating good flux calibration. These are plotted against a polynomial fit of the Triplespec continuum. The Triplespec flux is somewhat higher than the IFU fluxes (~25%), the long slit takes in more disk light than the 3′3 IFU FOV, plus there is more scattered light in the IFU optical train. The spectral slopes are in good agreement; however, the H-band flux is somewhat lower than expected. This is probably due to flux calibration uncertainties. The optical spectrum of the central 3′3 from the WiFeS data cube is also plotted; the optical and IR continua are also smoothly continuous.

The point-spread function (PSF) for the instruments was estimated from the standard-star observations by fitting a 2D Gaussian to the collapsed standard-star cube. For the SINFONI observations, the AO correction was not applied for the star, to prevent saturation; the PSF was estimated using an alternative star with a different spatial sampling, observed on the same night. The resulting Gaussian fits are somewhat elliptical; we use the major-axis FWHM. The results are listed in Table 3, showing the FWHM PSF, in pixels, and angular and spatial resolution.

### 3.4. Instrumental Fingerprint

It is well known that IFUs can have “instrumental fingerprints” that are not corrected by the standard calibration techniques. Menezes et al. (2014, 2015) demonstrate this for SINFONI and NIFS data cubes; they use the Principal Component Analysis (PCA) tomography technique to characterize the fingerprints (which on SINFONI data cubes show broad horizontal stripes) and remove them. This is visible in our data cubes; we median-collapse all wavelengths and display on a logarithmic scale. In fact, we see two horizontal stripes at y-axis pixels 11–24 and 48–51, as shown in Figure 4, and note that this is different from the pattern found in Menezes et al. (2015). This fingerprint affects further results, especially for extinction measures. An attempt to apply the PCA technique to remove the fingerprints failed, as the fingerprint amplitude is comparable to the data and appeared strongly in the tomogram corresponding to eigenvector E1. As an alternative, we simply interpolated over the fingerprint in the y-axis direction at each spectral pixel. The resulting data cube median is also shown in Figure 4.

### 4. Results

#### 4.1. Continuum Emission

All image plots in this paper will use the same scale unless otherwise noted, i.e., FOV with 3.3 × 3′3 on a side (540 × 540 pc, 1 pixel = 8.2 pc), with north being up and east to the left. For the WiFeS optical images, the plots are for an FOV with 20′ on a side (3.3 × 3.3 kpc, 1 pixel = 164 pc). The R.A. and decl. values are given relative to the nuclear cluster center. Note the scale lengths of 0′/5 and 50 pc. Figure 5 presents the stellar light around the nucleus, showing the individual J-, H-, K-, and V-band surface brightness maps in units of magnitude per square arcsec. These were extracted from the respective data cubes by averaging over the 10 nm around filter effective wavelengths, dividing by the pixel area and converting to magnitude using the method described above.

In the IR, the nuclear region (labeled “N”) presents as a central clump with half-light radius of about 50 pc. There are three secondary features, a ridge at PA 240° extending about 90 pc (labeled “2”) and two local light maxima at PA/radius 73°/130 pc and 175°/125 pc (labeled “1” and “3”). The ridge extension has a hint of a spiral structure. These features are more prominent in the H and K bands than in the J band, which is
consistent with greater dust penetration at longer wavelengths. The $H$ band also has somewhat better observational resolution than the $K$ band. The flux density for the nuclear cluster can be estimated by fitting a 2D Gaussian to the $K$-band image (the least obscured data); this is $1.72 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{nm}^{-1}$. The Gemini Observatory flux-to-magnitude calculator gives a magnitude of 16.0 for the 2MASS $K$ filter. At the distance magnitude of 32.6 and the solar $K$-band magnitude of 3.28 (Binney & Merrifield 1998), this gives a luminosity $L = 9.0 \times 10^3 L_\odot$.

Comparing a Gaussian fit to each of the secondary features, the FWHM of each is comparable to or just marginally larger than that of the standard star; therefore, we cannot say that these clusters are resolved.

Stellar colors, indicative of population age and obscuration, are shown in the false-color continuum image (Figure 6, left panel), which was created by layering the $J$, $H$, and $K$ filter total flux values (using blue, green, and red colors, respectively). The individual images have been smoothed by a 2D Gaussian at 2 pixel width to remove pixelation; the colors have also been enhanced to bring out the salient features. The right panel of Figure 6 shows the $H$–$K$ magnitude; the $J$-band magnitude was not used, as the interpolation to remove the instrumental fingerprint obscures cluster "3." The $H$-band magnitude contours are overplotted, with the same values as in Figure 5; the nucleus and other cluster features have lower $H$–$K$ magnitudes, indicative of bluer (younger) stellar populations. The optical surface brightness from the WiFeS data shows a featureless bulge; the nucleus is offset like the Pan-STARRS $g$ image.

4.2. Stellar Kinematics

The stellar kinematics were investigated using the CO bandheads in the range 2293–2355 nm, using the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004). The Gemini spectral library of near-infrared late-type stellar templates from Winge et al. (2009) was used, specifically the NIFS sample version 2. The observed $K$-band data cube was reduced to the rest frame (using $z = 0.007277$, equivalent to a velocity of $2182\,\text{km s}^{-1}$) and normalized. Both the observations and template were trimmed to the wavelength range of 2270–2370 nm. We followed the example code for kinematic analysis from the code website.11 The “Weighted Voronoi Tessellation” (WVT; Cappellari & Copin 2003) was used to increase the S/N for pixels with low flux; we use the voronoi procedure in QiitsView. This aggregates spatial pixels in a region to achieve a common S/N. This needs both signal and noise maps; these are obtained from the fit and error of the stellar velocity dispersion value at each pixel calculated by the pPXF routine; in this case the S/N target was 250. Figure 7 displays the results. The velocity field has a range of ±40 km s$^{-1}$ and shows no sign of ordered rotation. The zero value of the velocity was set as the median value returned from the pPXF routine, in this case the S/N target was 250. Figure 7 displays the results. The velocity field has a range of ±40 km s$^{-1}$ and shows no sign of ordered rotation. The zero value of the velocity was set as the median value returned from the pPXF routine, in this case the S/N target was 250. The average velocity dispersion value at each pixel calculated by the pPXF routine; in this case the S/N target was 250. Please see Figure 7 for more details.

11 http://www-astro.physics.ox.ac.uk/~mxe/software/ppxf_python_2017-03-27.zip
EVB V Da 10 cm D = + -´-

The central square indicates the IR IFU FOVs. All values are in mag arcsec^2.

Figure 5. First, second, and third panels: J-, H-, and K-band surface brightness, respectively. Labels (in blue) are the nuclear cluster/disk (“N”), secondary clusters (“1” and “3”), and the ridge-like feature (“2”). The contour values are chosen to delineate the features. Fourth panel: optical (V) surface brightness—note the change of spatial scale. The central square indicates the IR IFU FOVs. All values are in mag arcsec^2.

Figure 6. Left panel: continuum three-color image (J = blue, H = green, K = red). Right panel: H–K color (in mag). The black contour plot is the H-band surface brightness, as per Figure 5 (second panel).

Figure 7. Stellar kinematics from CO bandheads. Left panel: velocity. Right panel: velocity dispersion. Values in km s^{-1}. The contours are the K-band flux, in the range 10%–90% in steps of 20% of the maximum value.

Ho (2013) gives $M_\star = 3.9\times10^5 M_\odot$. These rather wide error estimates indicate the possibility that there is no SMBH in the nucleus of this galaxy (within 1.4$\sigma$, 1.2$\sigma$, and 1.6$\sigma$, respectively). If a BH of that mass exists, the sphere of influence is less than 1 pc.

To confirm this small SMBH size, we fitted a Sérsic index to the 2MASS $K_S$ image using the Galfit3 application (Peng et al. 2009). This found an index of 0.824; using the relationship of Savorgnan et al. (2013), we derive $M_\star = 1.14(\pm0.25, +0.78)\times10^5 M_\odot$, compatible with the value derived from the stellar velocity dispersion.

Using the BH mass computed from the Graham et al. (2011) relationship, the X-ray luminosity, the relationship between X-ray and bolometric luminosity from Ho (2009) ($L_{\text{bol}} = 16 \times L_X (2–10 \text{ keV})$), and the Eddington luminosity ($L_{\text{Edd}} = 1.3 \times 10^{38} M_\odot M_\odot \text{ erg s}^{-1}$), we derive the Eddington ratio ($R_{\text{Edd}} = L_{\text{bol}} / L_{\text{Edd}} = 1.4 (3.3, -0.98) \times 10^{-2}$) and the corresponding accretion rate $M_{\text{acc}} = L_{\text{bol}} / c^2 \eta = 7.4 \times 10^{-5} M_\odot \text{ yr}^{-1}$ using the standard efficiency factor $\eta$ of 0.1.

4.3. Extinction

The $H–K$ reddening map can be extended and quantified by using measures of extinction, where the known ratio of a pair of emission lines is compared against observations and extrapolated to the $B–V$ extinction and $A_V$ (the absolute extinction in the V band). In general, the formula is as follows:

$$E_{B–V} = \alpha_{\lambda_1, \lambda_2} \log \left( \frac{R_{\lambda_1, \lambda_2}}{F_{\lambda_1} / F_{\lambda_2}} \right),$$

where $R_{\lambda_1, \lambda_2}$ is the intrinsic emissivity ratio of the two lines and $\alpha_{\lambda_1, \lambda_2}$ extrapolates from the emission-line wavelengths to $B–V$.

From the Cardelli et al. (1989) reddening law, $A_V = R_V \times E_{B–V}$, where $R_V$ is the extinction ratio. We use a value of $R_V = 3.1$, the standard value for the diffuse ISM. Following the Cardelli parameterization of the reddening law in the infrared, we derive (where the wavelengths are in nm)

$$\alpha_{\lambda_1, \lambda_2} = \frac{2.95 \times 10^{-5}}{(\lambda_2^{1.61} - \lambda_1^{1.61})}.\tag{2}$$

From our observations, we have several methods of deriving the extinction: the various ratios between hydrogen recombination lines, and between the [Fe II] emission lines at $\lambda = 1257$ and 1644 nm. The values of $\alpha_{\lambda_1, \lambda_2}$ and $R_{\lambda_1, \lambda_2}$ are given in Table 4 below for the individual line ratios.

The HI ratios for (Hα, Hβ, Paβ, Paγ, and Brγ) are determined by case B recombination and assuming an electron temperature $T_e = 10^4 K$ and a density $n_e = 10^3 \text{ cm}^{-3}$ (Hummer & Storey 1987). The intrinsic flux ratio is a weak function of both temperature and density. Over a range $5000 < T_e < 10,000 \text{ K}$ and $100 < n_e < 1000 \text{ cm}^{-3}$, this varies by only 5%.

As the [Fe II] lines 1644 nm and 1257 nm share the same upper level, $a^4 D \rightarrow a^4 D$ and $a^4 D \rightarrow a^4 F$, respectively, their ratio is a function purely of the transition probabilities and
Figure 8. Emission-line fluxes used for deriving extinctions. The blue cross indicates the nucleus. Flux values (shown in color bar, plotted in log scale) are in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Contours are 0.1, 0.25, 0.5, and 0.75 of the maximum flux. The color bars have the maximum and minimum levels scaled so that zero extinction will have the same level for the [Fe II] and H I pairs.

Table 4
Extinction Calculation Parameters for Equation (1)

| Spectral Lines | $\alpha_{K_{\lambda}}$ | $R_{K_{\lambda}}$ | Avg | Max | Min |
|----------------|----------------------|-----------------|-----|-----|-----|
| Paβ/Brγ        | 5.22                 | 5.88            | 3.7 | 5.9 | 2.0 |
| [Fe II] λ1257/λ1644 | 8.21            | 1.36            | 3.6 | 5.8 | 1.4 |
| Paγ/Paβ       | 10.32               | 0.55            | 2.8 | 4.2 | 1.5 |
| Hβ/Hα         | 1.63                | 0.35            | 0.8 | 1.6 | 0.2 |

Note. $A_V$ for the IR spectral lines is for a circle of 100 pc radius around the nucleus, with maximum and minimum values at 5th and 95th percentile, respectively, to remove extrema. For the optical lines (Hα/Hγ) the values are for the inner $3 \times 3''$. The values of intrinsic emissivity ratio from the literature are discrepant; a value of 1.36 is derived from Nussbaumer & Storey (1988) Einstein coefficients, while the values from Quinet et al. (1996) give a value of 1.03, which decreases the derived $E_{B-V}$ value by 1 mag and the $A_V$ value by about 3 mag (see further discussion in Koo et al. 2016; Hartigan et al. 2004; Smith & Hartigan 2006). Using the value of 1.36 brings the extinction derived from the [Fe II] ratio into line with that from the H I ratio, so it will be adopted. The flux values are derived as described in Section 4.4 below. The visual extinction is derived as above, and the galactic foreground extinction of 0.16 mag (Burstein & Heiles 1982) is subtracted from the derived extinction. The emission-line fluxes used to derive the extinctions are shown in Figure 8. The maps are presented in Figure 9, showing the $A_V$ as derived from the various line ratios. The average, maximum, and minimum values derived from the various line ratios are shown in Table 4. The IR spectral lines, the average values show close agreement, with some variances in the extrema; the plots show patchy extinction, but none of the methods line up spatially with each other. We hypothesize that this is caused by several effects:

1. The [Fe II] and H I emissions come from gas in different excitation states that are not co-located and therefore have different LOS optical depths.
2. The Paβ/Brγ and the [Fe II] emissions are measured from different data cubes with pixel-to-pixel variations from both alignment and calibration. These are also subject to the instrumental fingerprint mentioned above.
3. The Paγ/Paβ ratios (which presumably do not suffer from calibration problems) are sensitive to flux measurement errors, which cause large variations since the wavelengths are close together. That noted, this ratio has the smallest variation over the whole field, being 2.2 mag in $A_V$ (0.7 in $E_{B-V}$).

Since there is no definitive pattern of extinction, we will use a single average value ($A_V = 3.4$) over the whole field to derive the extinction correction. Using the Cardelli reddening law, the ratio $A_V/A_B$ is 0.287, 0.178, and 0.117 (an increase in surface brightness of 0.97, 0.60, and 0.40 mag) for the J-, H-, and K-band filters, respectively. The dereddened $H-K$ map values are reduced by only 0.2 mag.

Extinction measures derived from emission lines are usually higher than those for stellar populations; Calzetti et al. (1994) found that Hβ/Hα extinction was a factor of 2 higher than the continuum extinction, due to hot stars being associated with dusty regions. Riffel et al. (2006a), in the 0.8–2.4 μm atlas of AGNs, show poor correlation between the total extinction derived from [Fe II] and that from H I ratios, especially for starburst galaxies. This seems to apply equally for a point-by-point comparison for this object. We note that the Balmer-decrement-derived extinction is significantly lower than the
panels, the contour plot is the same range. The contour plot in the IR ratio panels is the H-band flux, with the contours being 0.1−0.9 in steps of 0.2 of the maximum flux. For the visual ratio panels, the contour plot is the V-band flux with the same steps. Note the different axis scale for the V-band maps.

Figure 9. Extinction maps, using the emission-line flux ratios as labeled. The color bars give the $A_V$ value in magnitudes, with the infrared and visual ratios scaled to the same range. The contour plot in the IR ratio panels is the $H$-band flux, with the contours being 0.1−0.9 in steps of 0.2 of the maximum flux. For the visual ratio panels, the contour plot is the V-band flux with the same steps. Note the different axis scale for the V-band maps.

Table 5

| Species | $\lambda$ (nm) (Air) | $\lambda$ (nm) (Obs) | $F_1$ | $e_F_1$ | $F_2$ | $e_F_2$ | $F_3$ | $e_F_3$ |
|---------|---------------------|---------------------|-------|---------|-------|---------|-------|---------|
| Pa$\gamma$ | 1094.1 | 1102.1 | 23.24 | 0.39 | 17.49 | 0.24 | 11.29 | 0.16 |
| [P II] | 1188.6 | 1197.2 | 1.45 | 0.12 | 1.03 | 0.10 | 0.74 | 0.10 |
| [Fe II] | 1256.7 | 1265.8 | 3.31 | 0.15 | 3.80 | 0.11 | 3.16 | 0.07 |
| Pa$\beta$ | 1282.2 | 1291.5 | 40.27 | 0.06 | 31.22 | 0.39 | 21.04 | 0.34 |
| [Fe II] | 1533.5 | 1544.7 | 0.66 | 0.11 | 0.60 | 0.07 | 0.40 | 0.05 |
| [Fe II] | 1643.6 | 1655.6 | 2.27 | 0.13 | 2.91 | 0.13 | 2.55 | 0.09 |
| H$2$ 1-0S(9) | 1687.7 | 1700.0 | 0.40 | 0.11 | 0.25 | 0.08 | 0.07 | 0.04 |
| He I | 2059.7 | 2074.7 | 5.82 | 0.14 | 4.01 | 0.12 | 2.86 | 0.12 |
| H$2$ 2-1S(3) | 2073.5 | 2088.6 | 0.10 | 0.03 | 0.09 | 0.02 | 0.08 | 0.02 |
| H$2$ 1-0S(1) | 2121.3 | 2136.7 | 3.23 | 0.04 | 2.94 | 0.04 | 0.35 | 0.02 |
| Br$\gamma$ | 2166.1 | 2181.9 | 7.57 | 0.27 | 5.60 | 0.21 | 4.01 | 0.22 |
| H$2$ 1-0S(0) | 2223.3 | 2239.5 | 0.30 | 0.02 | 0.13 | 0.02 | 0.12 | 0.02 |
| H$2$ 2-1S(1) | 2247.7 | 2264.1 | 0.18 | 0.03 | 0.09 | 0.02 | 0.11 | 0.02 |
| H$2$ 1-0Q(1) | 2406.6 | 2424.1 | 0.29 | 0.03 | 0.34 | 0.04 | 0.39 | 0.02 |

Note. Flux values are in $10^{-16}$ erg cm$^{-2}$ s$^{-1}$.

4.4. Gas Fluxes, Kinematics, Excitation, and Star Formation

To obtain maps of the gas emission fluxes and kinematics, we used the velmap (velocity map) procedure in QFitsView. To improve S/N, especially in the velocity and dispersion measures, we applied the WVT method; the signal and noise measures are the Gaussian peak height and error, respectively. The WVT target S/N for Br$\gamma$, [Fe II], and H$2$ was 40, 30, and 10, respectively. There were residual poor fits from noisy pixels; these were interpolated over from surrounding values on each of the derived parameters.

4.4.1. Nebular Emission

Table 5 shows the relevant emission-line fluxes that were measured at three locations, the nucleus and the locations of the [Fe II] and H$2$ maxima. The absence of high-ionization species flux indicates a lack of X-ray emission from an AGN; specifically, [Ca vII] 2321 nm with ionization potential (IP) = 127 eV is not present. Similarly, Table 6 shows the optical emission line fluxes.

Figure 10 presents the maps of emission-line fluxes and equivalent widths (EWs) for the main species; each column is labeled with the species and rest-frame wavelength. The EW is calculated by dividing the flux in the emission line by the height of the continuum.

4.4.2. Excitation

Emission-line excitation broadly falls into two categories: (1) photoionization by a central, spectrally hard radiation field (an AGN) or by young, hot stars; or (2) thermal heating, which can be by either shocks or X-ray heating of gas masses. It has been shown (Larkin et al. 1998; Rodríguez-Ardila et al. 2005) that the nuclear activity for emission-line objects can be separated by a diagnostic diagram, where the log of the flux ratio of H$2$(2121 nm)/Br$\gamma$ is plotted against that of [Fe II]($\lambda1257$ nm)/Pa$\beta$. Following the updated limits from Riffel et al. (2013a), the diagram is divided into three regimes: star-forming (SF) or starburst (SB) (H$2$/Br$\gamma$ < 0.4, [Fe II]/Pa$\beta$ < 0.6), AGN (0.4 < H$2$/Br$\gamma$ < 6, 0.6 < [Fe II]/Pa$\beta$ < 2), and LINER (H$2$/Br$\gamma$ > 6, [Fe II]/Pa$\beta$ < 2). The diagnostic emission lines are convenient; the pairs are close together in wavelength, removing the dependency on calibration accuracy and differential extinction.

Figure 11 maps the ratios for each pair of emission lines. Specific locations of interest are also plotted with symbols; the nucleus, the H$2$ and [Fe II] flux maxima, and clusters “1” and
3" from the continuum plots. The \([\text{Fe}\ II]/\text{Pa}\beta\) ratio has a range of 0.03–0.44, with the lowest value in the center and the highest value in the SW region, located about 215 pc from the center. The \(H_2/Br\gamma\) ratio has a range of 0.03–0.37, with a similarly located peak to the SW.

Figure 11 also plots the density diagram for the values at each spaxel of \(\log([\text{Fe}\ II]/\text{Pa}\beta)\) against \(\log(H_2/Br\gamma)\), with the excitation mode regions (SF, AGN, and LINER) delineated and with the locations of interest plotted with symbols. The straight-line fit to the points (blue line in Figure 11) is

\[
\log([\text{Fe}\ II]/\text{Pa}\beta) = 0.558(\pm 0.1) \times \log(H_2/Br\gamma) - 0.130(\pm 0.091).
\]

The high correlation coefficient \((r = 0.79)\) indicates that this relationship can be used to determine the excitation mode from just one set of measurements, e.g., from the \(J\)-band spectrum when \(K\) band is not available.

Similarly, Figure 12 plots the BPT excitation diagram and the spaxel density diagram for the optical, as defined in Kewley et al. (2006), using the \([\text{N}\ II]/\text{H}\alpha\) and \([\text{O}\ III]/\text{H}\beta\) flux ratios.

### 4.4.3. Gas Kinematics

Figure 13 presents maps of the line-of-sight (LOS) velocities and dispersions of the main species: \(Br\gamma\) \((\lambda 2166 \text{ nm})\), \([\text{Fe} \ II]\) \((\lambda 1644 \text{ nm})\), and \(H_2\) \((\lambda 2121.5 \text{ nm})\). All LOS velocities have been set so that the zero is the median value. We also present the maps for \(H\alpha\) (Figure 14), showing the flux, EW, LOS velocity, and LOS dispersion. We compared the systemic velocity fields of the stars and gas from the central wavelength average around the nucleus, after reduction to rest frame; these vary from \(+7\) km s\(^{-1}\) \((Br\gamma)\) to \(+40\) km s\(^{-1}\) (stars). These are all within the measurement error \((\pm 55\) km s\(^{-1}\) for NIFS and \(\pm 125\) km s\(^{-1}\) for SINFONI).

### Table 6

| Species   | \(\lambda\) (Vac) (Å) | \(\lambda\) (Obs) (Å) | Flux \((10^{16} \text{ erg cm}^{-2}\text{ s}^{-1})\) | eFlux |
|-----------|-----------------------|-----------------------|---------------------------------|-------|
| [O II]    | 3727.1                | 3754.2                | 47.30                           | 2.88  |
| H\gamma   | 4341.7                | 4373.3                | 10.36                           | 0.85  |
| H\beta    | 4862.7                | 4898.1                | 27.87                           | 0.78  |
| [O III]   | 4960.3                | 4996.4                | 15.13                           | 0.38  |
| [O III]   | 5008.2                | 5044.7                | 32.19                           | 0.84  |
| He I      | 5877.3                | 5920.1                | 5.00                            | 0.29  |
| [O I]     | 6302.0                | 6347.9                | 1.95                            | 0.09  |
| [N II]    | 6459.8                | 6597.5                | 10.98                           | 1.12  |
| H\alpha   | 6546.4                | 6612.4                | 164.60                          | 5.38  |
| [N II]    | 6585.2                | 6632.3                | 30.62                           | 0.91  |
| He I      | 6680.0                | 6728.6                | 1.99                            | 0.17  |
| [S II]    | 6718.3                | 6767.2                | 11.02                           | 0.37  |
| [S II]    | 6732.7                | 6781.7                | 10.87                           | 0.35  |
| [S III]   | 9071.1                | 9137.1                | 21.86                           | 0.59  |

**Note.** Flux values are in \(10^{-16} \text{ erg cm}^{-2}\text{ s}^{-1}\).

Heliocentric corrections for different observations dates were \(<7\) km s\(^{-1}\).

### 4.4.4. Channel Maps

In order to map the flux distributions at all velocities covered by the emission-line profiles and to assist in delineating gas flows, we construct channel maps along the profile of the \(Br\gamma\), \([\text{Fe} \ II]\) \(\lambda 1644\) nm, and \(H_2\) emission. The maps were constructed by subtracting the continuum height, derived from the velocity map function \(\text{velmap}\), from the data cube. The spectral pixels are velocity binned and smoothed to reduce noise. Figures 15, 16, and 17 show the derived channel maps for \(Br\gamma\), \(H_2\), and \([\text{Fe} \ II]\) \(\lambda 1644\) nm,
Figure 11. Excitation diagram—-infrared. Left panel: flux ratio [Fe II]/Paβ, with H-band flux overplotted with white contours. Middle panel: H/$\gamma$. Right panel: excitation map of log-log plot of flux ratios. Contour levels at 1%, 5%, 10%, and 50% of maximum. The locations of interest are shown with symbols in the middle and right panels. The straight-line fit to the data is plotted as a blue dashed line; the fit from Riffel et al. (2013a) is plotted as a green dashed line.

Figure 12. Excitation diagram—optical. Left panel: flux ratio [N II]/H$\alpha$ (V-band flux overplotted in contours of 10%, 30%, 50%, 70%, and 90% of maximum). Middle panel: [O III]/H$\beta$ (white square is FOV of the IR IFU instruments, for comparison). Right panel: excitation map of log-log plot of flux ratios. Contour levels are at 1%, 5%, 10%, and 50% of maximum.

Figure 13. LOS velocity and dispersion for Br$\gamma$, [Fe II] $\lambda$1656 nm, and H$\beta$. Top row: velocity. Bottom row: dispersion. Right panels: velocity and dispersion histograms. All values are in km s$^{-1}$. 
Figure 14. Hα flux and kinematic maps. Top left: flux (units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$) (V-band flux overlapped in contours of 10%, 50%, 50%, 70%, and 90% of maximum). Top right: equivalent width in nm. Bottom left: LOS velocity. Bottom right: LOS dispersion.

respectively. The [Fe II] λ1644 nm line is used rather than the [Fe II] λ1257 nm line, because of the J cube instrumental fingerprint. Note that the fluxes are rescaled on each map to bring out the structure, rather than sharing a common scale across all maps.

5. Discussion

5.1. Black Hole Mass and Stellar Kinematics

The stellar kinematic results presented above show no ordered rotation and have a flat velocity dispersion structure. We can therefore conclude that in the central region, the stellar dynamics are either face-on or pressure supported. The first is favored from the associated gas dynamics (see below) and the fact that this object is an S0 galaxy, which will have stellar rotation.

From Hα (2008), the X-ray luminosity indicates a spectral class somewhere between Seyfert 1 and 2. The measured $R_{\text{Hβ}}$ is somewhat high for this class range, but this could be due to the uncertainties in the $M_e$ measurement, plus emission from SN remnants and unresolved point sources, e.g., high-mass X-ray binaries (Mimeo et al. 2013). This could be the major component of the X-ray emission, with minimal contribution from any SMBH. We note also that the uncertainties in $R_{\text{Hβ}}$ are not inconsistent with a value of zero, i.e., with no SMBH luminosity and X-ray emission solely from SF.

5.2. Emission-line Properties and Diagnostics

The Brγ and He I EWs show a similar structure; there is relatively less SF in the nuclear cluster, with the peak being in a rough ring about 50–80 pc from the center. The [Fe II] and H2 maximum values track their respective flux structures; the central “hole” is also visible in these maps. The [Fe II] and [P II] λ1886.6 nm emission lines can be used to diagnose the relative contribution of photoionization and shocks (Storchi-Bergmann et al. 2009), where ratios of ~2 indicate photoionization (as the [Fe II] is locked into dust grains), with higher values indicating shocked release of the [Fe II] from the grains (up to 20 for supernova remnants [SNRs]). The flux ratio over the field varies from 2.7 in the nucleus to 7.4 at the highest excitation ratio [Fe II]/Paβ location (in the SW corner of the field); this indicates that photoionization is the main excitation mode over most of the field, with an increased shock contribution at the more AGN-like excitation locations.

To determine the electron density, we use the ratio [Fe II]λ1533/1644 and the method of Storchi-Bergmann et al. (2009). Using the diagrams in that paper’s Figure 11, we measured this ratio over a region of 0.25 $\times$ 0.25 at the nucleus (0.27 ± 0.05) and at the location of the maximum [Fe II] emission (0.19 ± 0.02), deriving values of ~32,000 cm$^{-3}$ (nucleus) and 8000 cm$^{-3}$ ([Fe II] maximum). Over the whole field, the [Fe II] λ1533 nm flux was difficult to determine (having considerable noise), but values in the range 14,000 cm$^{-3} < n_e < 60,000$ cm$^{-3}$ are obtained where it can be measured. These values are consistent with their findings for NGC 4151. We can also use the ratio [Fe II]λ1533/1257 (Nussbaumer & Storey 1988) and obtain similar values, 10,000 < $n_e$ < 32,000 cm$^{-3}$.

To determine whether H2 excitation results from soft-UV photons (from SF) or thermal processes (from shocks or X-ray heating), we use the line ratio H2$\lambda$2247.7/λ1212.18 (Riffel et al. 2006b). This has a value of ~0.1–0.2 for thermal and ~0.55 for fluorescent processes. At the location of the maximum H2 flux, the ratio is measured as 0.21 ± 0.06, indicating thermal processes. Since AGN-like excitation is minimal over the whole field and therefore X-rays from an accretion disk heating are absent, we conclude that shocks are the main excitation mode for H2. The line H2 2–1 S(3) (λ2073.5 nm) can also be used to investigate the H2 excitation. In the case of X-ray-irradiated gas, this line is expected to be absent (Davies et al. 2005). This line is present, supporting the assertion that shocks are the main excitation mechanism. Other H2 lines (λ1957 and λ2033 nm) to place on the Mouri (1994) diagrams were not present or outside the spectral range.

To determine the thermal excitation temperature for H2, we use the observed fluxes at the available emission. Following Wilman et al. (2005) and Storchi-Bergmann et al. (2009), the relationship is

$$\log \left( \frac{F_i}{A_i g_i} \right) = \text{constant} \times \frac{T_i}{T_{\text{exc}}},$$

where $F_i$ is the flux of the $i$th H2 line, $\lambda_i$ is its wavelength, $A_i$ is the spontaneous emission coefficient, $g_i$ is the statistical weight of the upper level of the transition, $T_i$ is the energy of the level expressed as a temperature, and $T_{\text{exc}}$ is the excitation temperature. This relation is valid for thermal excitation, under the assumption of an ortho/para abundance ratio of 3:1. The $A$, $g$, and $T_{\text{exc}}$ for each line were obtained from online data “Molecular Hydrogen Transition Data.”12

12 www.astronomy.ohio-state.edu/~depoy/research/observing/molhyd.htm
To improve the S/N, the spaxels in the K-band data cube were summed where the H$_2$ flux was greater than $0.5 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$, and the fluxes of the resulting spectrum were measured by fitting a Lorentzian curve to each spectral line. As seen in Figure 18, the observed fluxes fit the equation well (as shown by the fitted line). The resulting excitation temperature (the inverse of the fitted line slope) is $T_{\text{exc}} = 6135$ K. This is much higher than found for several Seyfert galaxies (e.g., Storchi-Bergmann et al. 2009; Riffel et al. 2010, 2014, 2015; Riffel & Storchi-Bergmann 2011), which are in the range of 2100–2700 K, and in fact is above the H$_2$ dissociation temperature of $\sim 4000$ K. However, following Wilman et al. (2005), we can postulate a two-temperature model, where the lower-excitation transitions are thermalized and the higher-excitation transitions come from hotter gas close to the dissociation temperature, nonthermal fluorescent emission in low-density gas, or excitation by secondary electrons in the cloud. If we separately fit to the lower- and higher-excitation lines, we derive temperatures of 1640 ± 470 K and 3330 ± 880 K, respectively. We can also compute the rovibrational temperatures from the ratios H$_2$ 1–0 S(0)/H$_2$ 1–0 S(2) and H$_2$ 2–1 S(1)/H$_2$ 1–0 S(1) (Busch et al. 2017) and derive $T_{\text{rot}}(i=1) = 530$ K and $T_{\text{vib}} = 3870$ K.

We can also calculate the electron temperature and density from the optical spectrum, using the method of Kaler (1986) for the temperature from the [N II] $I(\lambda 6548 + \lambda 6584)/I(\lambda 5754)$ ratio and the method of Acker & Jaschek (1986) for the density from the [S II] $I(\lambda 6717)/I(\lambda 6731)$ ratio. In the inner 2″, the temperature is $\sim 8630$ K and the density is $\sim 670$ cm$^{-3}$. In the annulus from 2″ to 5″, the temperature and density calculations are more uncertain, due to the weakness of the [N II]$\lambda 5754$ line; they are $7500 \pm 2500$ K and $280 \pm 40$ cm$^{-3}$, respectively.

5.3. Gas Masses

We can derive the gas column density from the visual extinction value. The gas-to-extinction ratio, $N_{\text{H}}/A_V$, varies from 1.8 (Predehl & Schmitt 1995) to $2.2 \times 10^{21}$ cm$^{-2}$ (Ryter 1996); we will use a value of $2.0 \times 10^{21}$ cm$^{-2}$. We thus derive the relationship

$$
\sigma_{\text{Gas}} = 22.1 A_V M_\odot \text{ pc}^{-2}
$$

Using the extinction map from the Pa$\gamma$/Pa$\beta$ ratio, we derive the total gas mass in the central region, as given in Table 7 below. We also derive the ionized hydrogen and warm/hot and cold H$_2$ gas masses, using the formulae from Riffel et al. (2013b, 2015):

$$
M_{\text{H II}} \approx 3 \times 10^{13} F_{\text{IR}} d^2 M_\odot
$$

$$
M_{\text{H}_2(\text{hot})} \approx 5.0776 \times 10^{13} F_{\text{H}_2} d^2 M_\odot
$$
where $d$ is the distance in Mpc and $F$ is measured in erg cm$^{-2}$ s$^{-1}$. The H$_2$ flux is that of the 2121 nm line. The cold-to-warm molecular gas mass ratio ($7.2 \times 10^5$) is originally derived in Mazzalay et al. (2013) from the observed CO radio emission with estimates of CO/H$_2$ ratios (which can vary over a range of $10^5$–$10^7$); the figures derived in Table 7 for the cold H$_2$ are therefore only an estimate.

The cold H$_2$ mass estimate is greater than the ISM mass as derived from extinction, even at the lower estimate of the scaling relationship with warm H$_2$. This could be because in this environment the dust grains that cause the extinction are being evaporated by the SF photoionization, thus reducing the gas-to-dust/extinction ratio and underestimating the ISM mass.

Schönell et al. (2017) summarize results for one LINER, five Seyfert 1, and four Seyfert 2 galaxies observed by the AGNIFS group; the range of H II surface densities is 1.5–125 $M_\odot$ pc$^{-2}$, and the range of H$_2$ (cold+warm) surface densities is 526–9600 $M_\odot$ pc$^{-2}$. Our values (64 and 540 $M_\odot$ pc$^{-2}$, respectively) are within these ranges, with the H$_2$ value on the lower end of the range.

### 5.4. Star Formation and SNe

In this object, SF and SNe supply the bulk of nonstellar emission, with minimal AGN activity. We can derive the SF rates, using the relationship between SF rate and hydrogen recombination lines from Kennicutt et al. (2009), which is regarded as an “instantaneous” trace of SF. Assuming Case B recombination at $T_e = 10^4$ K and applying the line strength ratios, we get

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 5.66 \times 10^{-40} L(\text{Br}\gamma) \text{ [erg s}^{-1}].$$

The results are shown in Table 8.

The SF rates given in Table 2 above are mostly within a factor of 2, which is also in good agreement with the Br$\gamma$-derived rate as in Table 8. The exceptions are the WISE W4 and the X-ray-derived values. The WISE color–color diagram (Wright et al. 2010) places this object in the starburst/LIRG region. The X-ray flux from the nucleus could include AGN activity, which would reduce the derived SFR. There may be substantial highly obscured SF, which would only manifest in far-IR and X-rays, which penetrate the dust. From the SED fitting, the derived SFR is about $\sim 1.1 M_\odot$ yr$^{-1}$. The SFR derived from the radio flux is in excellent agreement with the other indicators, showing that there is no AGN component emission. The origin of radio emission from radio-quiet quasars
has been debated; Herrera Ruiz et al. (2016) find that this can come from the AGN. This object provides a counterexample.

Rosenberg et al. (2012) present a formula for the SN rate, based on the measured $\text{[Fe II]} \lambda 1257$ nm flux. SNR shock fronts destroy dust grains by thermal sputtering, which releases the iron into the gas phase, where it is singly ionized by the interstellar radiation field. In the extended post-shock region, $\text{[Fe II]}$ is excited by electron collisions (Mouri et al. 2000), making it a strong diagnostic line for tracing shocks. Their relationship is

$$\log(\nu_{\text{SNR}} [\text{yr}^{-1} \text{pc}^{-2}]) = (1.01 \pm 0.2) \log(L_{\text{[Fe II]}1257} [\text{erg s}^{-1} \text{pc}^{-2}]) - 41.17 \pm 0.9.$$  \hspace{1cm} (10)

The results, using the dereddened $\text{[Fe II]}$ flux, are shown in Table 8.

The SN rate derived from radio emission using the indicator from Condon (1992) can be compared with that derived from the $\text{[Fe II]}$ flux, above. For the VLSS (1.4 GHz) and TGSS (150 MHz) fluxes, $\nu_{\text{SNR}} = 0.089$ and 0.035 yr$^{-1}$, respectively. These are higher than the value from the $\text{[Fe II]}$ flux of 0.0083 yr$^{-1}$; however, the radio values are for the whole galaxy, not just the inner 500 pc.

The SF rate for the whole field given above can be compared with the rate derived from the WiFeS data. The H$\alpha$ flux from the nuclear $3'' \times 3''$ is $1.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, giving an emitted flux of $2 \times 10^{-39}$ erg s$^{-1}$. The SFR is determined by (Kennicutt et al. 2009)

$$\text{SFR}(M_\odot \text{yr}^{-1}) = 5.5 \times 10^{-42} L_{\text{H}\alpha} [\text{erg s}^{-1}]$$  \hspace{1cm} (11)

giving $1.1 M_\odot \text{yr}^{-1}$, in excellent agreement with the IR-derived value.

5.5. Stellar Population

Correcting the $H-K$ color map for the average visual extinction of 3.4 mag decreases the values by 0.2 mag; 95% of the pixels are in the range 0.37–0.58. Given the uncertainties about the absolute flux calibration of the data cubes, we are cautious about assigning a stellar type to the colors (e.g., the tables of Bessell & Brett 1988); however, the relative differences are clear, with the clusters about 0.3–0.4 mag bluer than the rest of the field. The average color over the central nucleus is 0.26, the color of an M star. Persson et al. (1983), in a study of clusters in the Magellanic Clouds, showed that an admixture of luminous, intermediate-age ($\lesssim 8 \times 10^9$ Myr) carbon stars can cause very red $H-K$ colors.
Table 7
Gas Masses, Masses within the Maximum Value Pixel, within 100 and 200 pc of Center, and over the Whole Field, plus the Surface Density within the Central 100 and 200 pc

| Species       | Max. Pixel<sup>a</sup> M<sub>v</sub> pc<sup>−2</sup> | M<sub>v</sub> (100pc) | M<sub>v</sub> (200pc) | M<sub>v</sub> (Total)<sup>b</sup> | M<sub>v</sub> pc<sup>−2</sup> (100 pc) | M<sub>v</sub> pc<sup>−2</sup> (200 pc) |
|---------------|-----------------------------|-----------------|-----------------|----------------|----------------|----------------|
| ISM (HI)      | 101                        | 2.0 × 10<sup>6</sup> | 6.1 × 10<sup>6</sup> | …              | 63.7           | 48.8           |
| H II          | 8.5                        | 2.0 × 10<sup>6</sup> | 3.4 × 10<sup>6</sup> | 3.7 × 10<sup>6</sup> | 63.7           | 27.1           |
| H<sub>2</sub> (warm) | 7.1 × 10<sup>−5</sup>                        | 23.3            | 46              | 49              | 7.4 × 10<sup>−4</sup> | 3.7 × 10<sup>−4</sup> |
| H<sub>2</sub> (cold) | 51.1                        | 1.7 × 10<sup>7</sup> | 3.3 × 10<sup>7</sup> | 3.5 × 10<sup>7</sup> | 541            | 264            |

Notes. Values are derived from Equations (5)–(8).
<sup>a</sup> Pixel with greatest flux or highest density.
<sup>b</sup> Over whole field where valid measurement.

The mass of the nuclear cluster can be estimated from the cluster size and velocity dispersion; using the virial formula,

\[
M \approx \frac{3}{2} \frac{\sigma^2 R}{G},
\]

where \( R \) is the cluster radius and \( \sigma^2 \) is the dispersion, and using the values of 50 pc and 44 km s<sup>−1</sup>, we derive a mass of \( \sim 3.4 \times 10^7 M_\odot \). This is a lower limit; any rotation will support more mass, and the stars are probably not settled into virial equilibrium. Simulations (see Section 5.8) suggest that the stars settle into a thin disk, rather than a spherical cluster. Using the luminosity of 9.0 × 10<sup>7</sup> \( L_\odot \), calculated above, we get a mass-to-light ratio of \( \sim 0.38 \). This is again consistent with an old stellar population (with an \( M/L \) of about 1) mixed with younger SF.

In Balcells et al. (2007), the sizes of nuclear disks are measured by analyzing surface brightness profiles of S0–Sbc galaxies from Hubble Space Telescope NICMOS images. They find that the central star clusters are usually unresolved at \( \sim 10 \) pc resolution, whereas the nuclear disk sizes are found to be in the range of 25–65 pc (from their Table 4). It can be concluded that the central object visible in our observations is more likely to be a disk than a spherical structure.

The ratio of H II to He I emission can be used as an indicator of relative age of star clusters, following Böker et al. (2008); as the He I ionization energy is 24.6 eV versus 13.6 eV for hydrogen, the He I emission will arise in the vicinity of the hotter stars (B and O type), which will vanish fastest. Taking the ratio of the flux from Brγ and He I \( \lambda 2058 \) nm for the nuclear cluster and the two light concentrations and the ridge extension, the nuclear cluster shows a value of 0.72, while the other three show values of 0.60–0.63. Even though the differences are small, it is an indicator that the nuclear cluster is the youngest region.

We can estimate the stellar ages in the central region, using the methods of Brandl et al. (2012) and references therein, which examines the starburst ring in NGC 7552. They use the pan-spectral energy distribution of starburst models of Groves et al. (2007) to derive cluster ages based on Brγ EW. The map for Brγ (in Figure 10) shows that the central cluster and surrounding region have an EW in the range of 2.5–4.5 nm, which translates to an age in the range of 5.9–6.1 Myr. This is compatible with the findings in Ohyama et al. (1997, and references therein), which derive the age from the I(He II \( \lambda 4686 \))/I(Hβ) versus EW(Hβ) starburst model diagram. We can also derive the Lyman continuum flux, \( N_{L_\gamma} \approx 1.8 \times 10^{52} \) s<sup>−1</sup>, and the number of O7V-type stars, \( N_{O7V} \approx 3200 \), within a radius of 50 pc from the peak emission, using the scaling relationships cited in Brandl et al. (2012). This mixture of old and new stars in the nuclear cluster is by no means unique to this object; this is the case in our own Galaxy (Do et al. 2009) and in NGC 4244 (Seth et al. 2008).

We can hypothesize that the starburst proceeded outward from the center in a wave, with shock winds from the young stars triggering SF farther out. This would also be supported by the observation that the [Fe II] flux seems to surround the H II region. The ratio of the EW of He I versus Brγ, for the 150 pc around the nucleus, shows a lower value in the center (1.3–1.5) surrounded by a ring of higher value (1.9–2.1), also indicating a younger stellar population. One could also hypothesize a period of AGN activity providing the initial compression wave.

5.6. Excitation Mechanisms

The IR excitation diagram (Figure 11, right panel) shows that almost all pixels are within the “Starburst” regime, with minimal identifiable AGN activity (the pixels in the AGN region are located with low absolute flux values, with some corresponding uncertainty). The locations of interest, which are...
the superwind to be at or nearly face-on to our LOS, which would also explain the lack of any ordered stellar rotation, observed (see Figure 7). The Brγ and [Fe II] velocity and dispersion fields are virtually identical, in both structure and distribution. The Brγ velocity distribution (as shown in the velocity histogram) is somewhat bimodal, peaking around ±10 km s⁻¹. We suggest that most of the HI gas is in motion and that the apparent velocity at any point is just the mass-weighted sum of the motions toward and away from us. The histograms also show that the H₂ velocity and dispersion are kinematically colder, with the dispersion peak at 30 km s⁻¹, half that of the Brγ and [Fe II]. The H₂ velocity distribution is also much lower.

The Brγ flux is strongly centrally concentrated, with the LOS velocity presenting a quadrupole pattern and with lower velocity dispersion in the center than at the periphery of the field. The [Fe II] flux is peaked at the periphery of the Brγ flux; this is compatible with the [Fe II] lines originating in less ionized material than the H I lines. The H₂ is kinematically different; the velocity and dispersion maps and distributions are kinematically cooler. The H₂ velocity map shows almost the same pattern as the Brγ map, but the N–NW positive velocity region is reduced; this suggests that the two are kinematically decoupled. This compares with Riffel et al. (2008) for NGC 4051, which also shows a similar channel map; they find the H₂ rotational structure to be dissimilar to the stellar rotation. Rodriguez-Ardila et al. (2004), in a sample of 22 mostly Seyfert 1 galaxies, suggest that [Fe II] and H₂ originate in different parcels of gas and do not share the same velocity fields, with the [Fe II] flux locations, velocities, and dispersions being different from those of H₂; our results support this view. Since IC 630 is close to face-on, it is difficult to determine whether the H₂ is in the Galactic plane.

The channel maps present a complex patchy picture (Figures 15–17). There is some evidence of structure in the NW (receding) to SE (approaching) directions. Given that the overall gas kinematics (Figure 13) do not show the signatures of either biconal outflow or rotation, we can hypothesize that we are observing the outflows face-on, with streamers of gas rather than the gas filling a complete cone. In this case, the observed structure is again just the mass-weighted sum of the motions. At the extreme velocities, the Brγ and [Fe II] maps are similar; the difference appears at low velocity, reflecting the overall flux distribution differences. The H₂ maps are dissimilar; they are kinematically colder. The filamentary structure is similar (though at a smaller scale) to the outflows seen in M82.

### 5.7. Gas Kinematics

#### 5.7.1. Velocity and Channel Maps

The LOS velocities do not show a simple bipolar structure that would be expected from disk rotation or outflow cones; instead, it shows complicated multiple regions of both approaching and receding gas. Ohyama et al. (1997) consider the superwind to be at or nearly face-on to our LOS, which would also explain the lack of any ordered stellar rotation, observed (see Figure 7). The Brγ and [Fe II] velocity and dispersion fields are virtually identical, in both structure and distribution. The Brγ velocity distribution (as shown in the velocity histogram) is somewhat bimodal, peaking around ±10 km s⁻¹. We suggest that most of the HI gas is in motion and that the apparent velocity at any point is just the mass-weighted sum of the motions toward and away from us. The histograms also show that the H₂ velocity and dispersion are kinematically colder, with the dispersion peak at 30 km s⁻¹, half that of the Brγ and [Fe II]. The H₂ velocity distribution is also much lower.

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#### 5.7.2. Outflows

Let us examine the geometry of the H II outflow. The half-light radius (i.e., the radius of a circle from the center that covers half the total flux in each channel) increases from 100 to 115 pc over the velocity range from 0 to ±270 km s⁻¹. Within uncertainties, we can model this as a cylinder, as the half-light radius expands with height, rather than shrinks as a spherical shell expansion would display. The centroid position does not move much, except at extreme velocities, where a patchy structure will have the greatest effect, showing that the outflow is nearly face-on; this will not affect the outflow calculation, as the flux is low at these velocities.

Calculating the flux times the velocity at each channel gives us a “momentum” measure; this is a maximum at ±90 km s⁻¹ (equivalent to 9 × 10⁻⁵ pc yr⁻¹ or 90 pc Myr⁻¹) and will be

---

### Table 8

| Parameter          | Max. Pixel | 100 pc | 200 pc | Total |
|--------------------|------------|--------|--------|-------|
| SFR (M₀ yr⁻¹)     | 2.1 × 10⁻⁴ | 0.44   | 0.77   | 0.83  |
| SNR (yr⁻¹ pc⁻²)  | 1.9 × 10⁻⁷ | 1.1 × 10⁻⁷ | 5.8 × 10⁻⁸ | 2.9 × 10⁻⁸ |
| SNR (yr⁻¹)       | 1.3 × 10⁻⁵ | 3.4 × 10⁻³ | 7.3 × 10⁻³ | 8.5 × 10⁻³ |
| SN Interval (yr)  | 7650       | 300    | 135    | 118   |

Note. Regions as for Table 7. The SNR is shown as the rate per year per pc², per year over the region and the interval between SN.
used to calculate the outflow. The radius of 90% of the flux for this channel is 205 pc, which is an area of $1.3 \times 10^5$ pc$^2$; the flux total in both channels is $10.4 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, and the channel width is 60 km s$^{-1}$, which is equivalent to 360 pc. Simplifying the geometry to a cylinder, this is a total volume of $9.5 \times 10^7$ pc$^3$ for both channels. We can calculate the mass of H II in the channel from Equation (6) above; this is $3.4 \times 10^5 M_\odot$, and the density is thus $3.6 \times 10^{-3} M_\odot$ pc$^{-3}$. From these values, we obtain $\dot{M} = 0.09 M_\odot$ yr$^{-1}$. This is in line with the studies of other outflows from Seyferts and LINERs ($0.01–10 M_\odot$ yr$^{-1}$; Riffel et al. 2015).

The maximum kinetic power of the outflow is at the velocity $v = +150$ km s$^{-1}$ ($1.8 \times 10^{38}$ erg s$^{-1}$) and $v = -210$ km s$^{-1}$ ($3.9 \times 10^{38}$ erg s$^{-1}$) channels. Integrating over all velocity channels, the total power is $1.8 \times 10^{39}$ erg s$^{-1}$. This is two orders of magnitude below the estimates for Mrk 1157 (Riffel & Storchi-Bergmann 2011) and NGC 4151 (Storchi-Bergmann et al. 2010) of 2.3 and $2.4 \times 10^{41}$ erg s$^{-1}$, respectively. These galaxies have significant AGN activity, rather than just SF, to generate larger outflows at higher velocities.

5.8. Simulations

M. Schartmann et al. (2017, in preparation) present simulations of the evolution of circumnuclear disks in galactic nuclei. 3D AMR hydrodynamical simulations with the RAMSES code (Teyssier 2001) are used to self-consistently trace the evolution from a quasi-stable gas disk. This disk undergoes gravitational (Toomre) instability, forming clumps and stars. The disk is subsequently partially dispersed via stellar feedback. The model includes a $10^7 M_\odot$ SMBH, with an $8.5 \times 10^9 M_\odot$ galactic bulge, and includes SN feedback, which drives both a low gas density outflow and a high-density fountain-like flow. It finds that the gas forms a three-component structure: an inhomogeneous, high-density, molecular cold disk, surrounded by a geometrically thick distribution of molecular clouds above and below the disk midplane and tenuous, hot, ionized outflows perpendicular to the disk plane.

SF continues until the disk returns to stability. This process cycles over $\sim 200$ Myr (depending on initial parameters); the starburst only consumes about half the gas, and further inflows will feed the central region until instability is reached and the process can start again. This scenario explains the observations of short-duration, intense, clumpy starbursts in Seyfert galaxies in their recent ($\sim 10$ Myr) history (Davies et al. 2007a). The results from Schartmann et al. show strong similarities to the IC 630 observations, with the initial formation of a few star clusters and clumps, and the outflows in filaments with a broad-based cone or cylindrical geometry reaching to similar scale heights of several hundred parsecs.

The channel map at 30 Myr (Figure 19) shows the filamentary structure as seen with IC 630, with coherent organization being traced through the velocity cuts.

Seth et al. (2008) proposed two possible nuclear cluster formation mechanisms: (1) episodic accretion of gas from the disk directly onto the nuclear star cluster, or (2) episodic accretion of young star clusters formed in the central part of the galaxy due to dynamical friction. The simulation results suggest that the second scenario is more likely; however, the simulation indicates that the clusters are destroyed and redistributed through relaxation to the global potential, rather than dynamical friction.

We can suggest a “life cycle” of nuclear gas and SF and AGN activity:

1. Gas flows into the nucleus of a galaxy, through minor mergers or tidal torques, e.g., bars, where it collects in a disk in the bulge (and/or SMBH) gravitational potential.
2. The gas disk becomes Toomre-unstable and starts collapsing into star-forming clumps and clusters. The SF rate peaks at about 6–30 Myr after the onset of instability. AGN activity may contribute to the instability.
3. Stellar feedback, including SNe and hot OB/W-R stellar winds, partially disperses the gas disk and drives filamentary outflows with a scale height of several hundred parsecs, with the maximum flow at about 10–30 Myr. These winds do not fuel any significant AGN activity (Davies et al. 2007b).
4. At about 150 Myr, SF declines, with the gas disk approaching Toomre stability within the following 20–30 Myr. The stars settle into a nuclear disk about 40–100 pc across.
5. AGB winds efficiently feed any SMBH, and AGN activity starts about 50–100 Myr after the starburst. The SMBH grows by this feeding and tidal friction infall from the gas disk. AGN outflows may trigger further SF, and the activity continues until all available gas is consumed.

We have caught IC 630 in the phase between the starburst and AGN activity.

6. Conclusions

We have mapped the gas and stellar flux distribution, excitation, and kinematics from the inner $\sim 300$ pc radius of the starburst S0 galaxy IC 630 using NIR $J$, $H$, and $K$-band integral-field spectroscopy at a spatial resolution of 37–43 pc.
(0\textdegree23–0\textdegree26), plus additional optical IFS. The main conclusions of this work are as follows.

1. The nuclear region has a central cluster or disk (half-light radius of 50 pc) with at least two other light concentrations (clusters) within 130 pc. The central stellar population is a mixture of young (∼6 Myr) and older stars.

2. The stellar kinematics show an SMBH of $M_\bullet = 2.25(-1.6, +5.1) \times 10^8 M_\odot$ (within 1.4σ of there being no central black hole). The AGN-like bolometric luminosity of the galaxy (radio and X-rays) is mostly from SF, rather than BH activity.

3. Within 200 pc of the nucleus the mass of the cold ISM, as derived from extinction, is $M_{\text{ISM}} \approx 6.1 \times 10^6 M_\odot$, the estimated cold molecular gas mass is $M_{\text{H}_2(\text{cold})} \approx 3.3 \times 10^8 M_\odot$, the mass of ionized gas is $M_{\text{H}_\alpha} \approx 3.4 \times 10^6 M_\odot$, and the mass of the hot molecular gas is $M_{\text{H}_\text{II}} \approx 46 M_\odot$. The cold H2 mass estimate is greater than that of the ISM as derived from extinction: SF photoionization and the high-excitation temperature may have sublimated the dust grains.

4. The SF rate is $0.8 M_\odot \text{yr}^{-1}$, with an SN rate of 1 per 135 yr in the central 200 pc, producing X-ray and radio emission and releasing iron from dust grains, which is subsequently photoionized and shock-heated.

5. Emission-line diagnostics show that the vast majority of gas excitation is due to SF, with minimal input from AGN activity. For the main species, H II is excited by UV photons from young stars, and [Fe II] is also photoionized from the young stars with minor contribution from shocks, whereas H2 is excited mainly by shocks, with possibly some contribution from X-ray heating from SF.

6. The [Fe II] and H1 emissions are closely coupled in velocity and dispersion, but the peak flux of the [Fe II] is at the periphery of the Brγ flux. The H2 is kinematically colder than the H I and is also spatially located differently than both the [Fe II] and H I.

7. A starburst ∼6 Myr ago provided powerful outflow winds, with the ionized gas outflow rate at 0.09 $M_\odot \text{yr}^{-1}$ in a face-on truncated cone geometry.

8. Our observations are broadly comparable with simulations where a Toomre-unstable gas disk triggers a burst of SF, peaking after about 30 Myr and possibly cycling with a period of about 200 Myr.

IC 630 is an example of a galaxy that has “AGN-like” activity (radio and X-ray emission) but displays minimal AGN excitation. Even though it is an S0 galaxy, it has a high SF rate both in the central region and over the whole galaxy. This object is an example of nuclear SF dominating the narrow-line region emission. The nuclear young stars and SNe provide photoionization, stellar winds, and shocks to excite the H I, H2, and [Fe II].

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