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Resolved nuclear CO(1–0) emission in APM 08279+5255: gravitational lensing by a naked cusp?

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ABSTRACT

The ultraluminous broad absorption line quasar APM 08279+5255 is one of the most luminous systems known. Here, we present an analysis of its nuclear CO(1–0) emission. Its extended distribution suggests that the gravitational lens in this system is highly elliptical, probably a highly inclined disc. The quasar core, however, lies in the vicinity of a naked cusp, indicating that APM 08279+5255 is truly the only odd-image gravitational lens. This source is the second system for which the gravitational lens can be used to study structure on sub-kiloparsec scales in the molecular gas associated with the AGN host galaxy. The observations and lens model require CO distributed on a scale of ~400 pc. Using this scale, we find that the molecular gas mass makes a significant, and perhaps dominant, contribution to the total mass within a couple of hundred parsecs of the nucleus of APM 08279+5255.

Key words: gravitational lensing – galaxies: active – quasars: individual: APM 08279+5255.

1 INTRODUCTION

Identified serendipitously in a search for high-latitude carbon stars, the $z = 3.9$ broad absorption line quasar APM 08279+5255 is coincident with an *IRAS* source with a flux of 0.95 Jy at 100 μm (Irwin et al. 1998). Observations with SCUBA reveal that APM 08279+5255 possesses a significant submillimetre flux of 75 mJy at 850 μm (Lewis et al. 1998), implying a bolometric luminosity of $\sim 5 \times 10^{15}\,L_\odot$. Imaging reveals that APM 08279+5255 is not point-like, but rather is extended over a fraction of an arcsecond with a structure indicative of gravitational lensing (Irwin et al. 1998). The composite nature of APM 08279+5255 was confirmed in adaptive optics (AO) images obtained by Ledoux et al. (1998), with the system appearing as a pair of point-like images separated by 0.4 arcsec. Observations with NICMOS on the *Hubble Space Telescope* (*HST*) (Ibata et al. 1999) and AO images taken with the Keck telescope (Egami et al. 2000) also uncovered a fainter third component between the brighter two. Gravitational lens models derived from these observations suggest that the quasar continuum source has been magnified by ~90.

Using IRAM, Downes et al. (1999) detected emission in CO(4–3) and CO(9–8), revealing the presence of warm circum-nuclear gas in APM 08279+5255. Papadopoulos et al. (2001) were able to search for CO(1–0) and CO(2–1) in this system using the Very Large Array (VLA). Both were clearly detected associated with the quasar nucleus, as well as a more extended component located several arcseconds from the quasar images. Using locally established values of the CO-to-H_2 ratio, this lone cloud represents $\sim 10^{11}\,M_\odot$ of cold and/or subthermally excited gas.

In this Letter, we present an analysis of nuclear CO(1–0) emission in APM 08279+5255 using the VLA at high spatial resolution (0.3 arcsec). The CO appears as a partial ring of ~0.6-arcsec diameter. These data suggest a total revision in the gravitational lens model for this source, with the new model involving a 'naked cusp', which naturally accounts for the observed odd number of images. They also imply that the nuclear CO must be spatially extended on a scale of at least 400 pc, making this the second source in which gravitational lensing can be used as a 'telescope' to explore sub-kiloparsec-scale structure of molecular gas in the active galactic nucleus (AGN) host galaxy.

2 OBSERVATIONS AND RESULTS

Observations of the CO(1–0) emission from APM 08279+5255 were made in 2001 March and April using the VLA in the B (10 km) configuration. A total of 20 h were spent on the source. Because of limitations with the VLA correlator, we chose to observe in continuum mode using two 50 MHz bandwidth intermediate frequencies (IFs), each with two polarizations. One IF was centred on the redshifted CO(1–0) line, corresponding to a frequency of 23.465 GHz, while the second IF was tuned away

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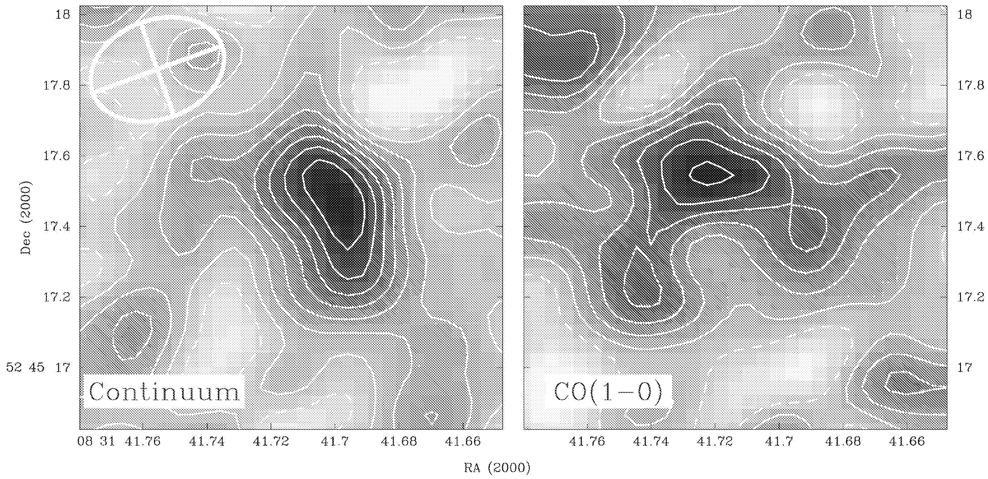

Figure 1. The 23-GHz continuum emission (left) and CO(1−0) line emission (right) in APM 08279+5255. The contours are at −1 (dashed), 0, 1... × σ. The image has been CLEANed and the ellipse in the upper corner of the left-hand panel represents the CLEAN beam. The quasar A image, as determined from NICMOS imaging, lies at J2000 $08^{\rm h}31^{\rm m}41\overset{\rm s}{.}64$, $52°45'17\overset{''}{.}5$, offset from the radio emission (Ibata et al. 1999). This is probably due to astrometric errors in the VLA and *HST* reference frames.

from the emission line to a frequency of 23.365 GHz. This observing set-up maximizes sensitivity since the effective bandwidth (45 MHz, 575 km $\rm s^{-1}$) closely matches the observed CO linewidth (Downes et al. 1999), but sacrifices velocity information (Carilli, Menten & Yun 1999). The source 3C 286 was used for absolute gain calibration. The rms noise on the final image is 35 μJy $\rm beam^{-1}$ with an effective spatial resolution of FWHM = $0.39 \times 0.28\ \rm arcsec^2$ with a major axis position angle of −70°. Fast-switching phase calibration was employed with a calibration duty cycle of 130 s (Carilli & Holdaway 1999). The phase stability for all the observations was excellent, such that the array was easily phase-coherent over the calibration cycle time. This was demonstrated by imaging the phase calibrator (0824 + 558) with a similar calibration cycle time, and by imaging the radio continuum emission from APM 08279+5255 itself.

The images of the line and continuum emission from APM 08279+5255 are shown in Fig. 1. The CO line image was generated by subtracting from the visibility data a CLEAN component model of the continuum emission made from the off-line data. The peak surface brightness for the continuum emission is 0.24 ± 0.035 mJy $\rm beam^{-1}$, with a total flux density of 0.41 ± 0.07 mJy. The corresponding numbers for the line emission are 0.183 ± 0.035 mJy $\rm beam^{-1}$ and 0.39 ± 0.09 mJy. The latter corresponds to a velocity-integrated line flux of 0.22 ± 0.05 Jy km $\rm s^{-1}$, consistent with 0.15 ± 0.045 Jy km $\rm s^{-1}$ deduced for the inner ~1 arcsec by Papadopoulos et al. (2001).

The continuum emission is extended north–south, with a position angle and spatial extent as expected based on the three-component optical gravitational lens. An attempt was made to decompose the continuum map into three point-like images, centred upon the positions derived from the analysis of *HST* images (Ibata et al. 1999). Given the image resolution, it was not possible cleanly to separate the northernmost images (A + C) which have a separation of ~0.15 arcsec. The relative flux of (A + C)/B ~ 1.5, quite similar to the optical ratio presented by Ibata et al. (1999). The line emission, on the other hand, shows distinct curvature away from the continuum position angle, and at the 3σ surface brightness level it appears as an almost complete ring with a diameter of about 0.6 arcsec. While the map of the line emission is of low signal-to-noise ratio, the ring-like structure is apparent in each of several days' worth of observations. Also, its size is in agreement with that of the CO(4−3) and CO(9−8) emission (Downes et al. 1999) and the CO(2−1) emission (Papadopoulos et al. 2001). Hence these observations reveal the gross features of the CO(1−0) emission, although more observations are required to uncover the finer details.

The observed CO(1−0) brightness temperature of the ring (averaged over ~575 km $\rm s^{-1}$) is 1.4 ± 0.8 K, which corresponds to an emitted brightness temperature of $T_{\rm b}$ ~ 7 K at z ~ 3.9. A lower limit for the magnification factor of the CO(1−0) emission can be derived assuming the warm gas emitting the high-J CO lines (Downes et al. 1999) to be also emitting the J = 1−0. This gas phase is optically thick with $T_{\rm kin}$ ~ 200 K, in agreement with the inferred dust temperatures (Lewis et al. 1998), which then yields a velocity-averaged filling factor of $f \sim 7/200 = 0.035$. Since differential lensing will 'boost' a compact warm region at the expense of a more extended and possibly subthermally excited gas phase that emits the CO(1−0), the true value of f will be larger.

3 GRAVITATIONAL LENSING

The lensing galaxy has yet to be identified in APM 08279+5255. Hence only the quasar positions and magnitudes are available to constrain any lensing model. Other than APM 08279+5255, all other lens systems possess an even number of images. Theoretically, any non-singular mass distribution should produce an odd number of lensed images (Burke 1981), and the ubiquity of even numbers of images has been used to limit the core radius in lensing systems, as small cores result in the demagnification of one of the images. Because of the brightness of the central source, however, models for APM 08279+5255 have required the opposite, a very circular model with a large core/shallow cusp (Lewis, Robb & Ibata 1999; Egami et al. 2000; Munoz, Kochanek & Keeton 2001). We further explore the lens model of APM 08279+5255 in light of the observations presented here.

The concordance between the optical images of APM 08279+5255 and the radio continuum at 3.6 cm (Ibata et al. 1999) and 23 GHz demonstrates that they come from coincident regions with a similar scalesize. Associated with the active core of APM 08279+5255, these regions are smaller than the gravitational lensing caustics. The quite different morphology displayed in the CO image, however, indicates that this emission arises in a larger region, distinct from the continuum radiation. With its extended nature, the CO-emitting region can lie under different parts of the caustic network. The CO source, however, cannot be significantly more extended than the caustic network, as the resulting image would not show the ring structure seen in Fig. 1. Therefore, for a given model, the size of the ring image provides a probe of the scalesize of the emitting region.

To form ring-like images, the source must be extended and cover a substantial fraction of the inner caustic structure of the lens; the resulting image appears as a ring, following the outer critical line in the image plane (see Kochanek, Keeton & McLeod 2001). Examining the critical line structure in all previously published models for APM 08279+5255 (Ibata et al. 1999; Egami et al. 2000; Munoz et al. 2001), the resulting structure for the Einstein ring of a source centred upon the quasar nucleus should be quite circular, with a radius of ~0.2 arcsec, passing through the two brighter quasar images; such images for an extended source can be seen in the models of Egami et al. (2000). This is quite different from the CO structure displayed in Fig. 1, with the CO emission clearly showing a roughly east–west extension, with the hole in the ring occurring ~0.5 arcsec from image A. Using the model derived from the *HST* data (Ibata et al. 1999), we have explored the image configurations for a range of sizes and shapes, centred upon the quasar source, for the CO-emitting region. None reproduces the observed image structure, and we reject this previous model.

Naked cusps occur in highly elliptical systems, such as flattened discs, when the inner diamond caustic extends outside the elliptical caustic. A source inside this extension produces three roughly collinear images of similar brightness (Maller, Flores & Primack 1997; Bartelmann & Loeb 1998; Keeton & Kochanek 1998; Moller & Blain 1998; Blain, Moller & Maller 1999; Bartelmann 2000). While gravitational lensing by spiral galaxies has been observed (e.g. B1600+434: Koopmans, de Bruyn & Jackson 1998), no observed lensed quasar system has so far been associated with a naked cusp.

To examine the possibility that the observed image configuration is due to gravitational lensing by a naked cusp, we have constructed a simple mass model. Following Bartelmann & Loeb (1998), this consists of a truncated flattened disc in a spherical halo. APM 08279+5255 has brightened considerably since its discovery (Lewis et al. 1999; Ofek, private communication, see http://wise-obs.tau.ac.il/ ~ eran/LM), potentially because of the effects of gravitational microlensing. Comparing the images obtained in 1998 (Ibata et al. 1999; Egami et al. 2000) and those obtained in 1999 (Munoz et al. 2001), the relative image brightnesses have changed appreciably, with image B changing from being 78 per cent as bright as image A to only 50 per cent in the latter epoch; such behaviour is extremely suggestive of the action of gravitational microlensing, although longer term monitoring is required to confirm this. Hence the relative image brightnesses cannot be used to constrain any mass model. Given the sparsity of constraints, we choose to find a model that can recover the image positions, while providing a reasonable description of the observed CO emission. As can be imagined, the parameter space is large, so a range of models that reproduced the quasar positions were chosen and then modelling of the CO emission was undertaken by eye. With this, therefore, we do not claim that the model presented here is unique, only consistent with the general form of data.

In our chosen model, the disc is highly inclined, presenting a projected axial ratio of 0.25, and the disc is truncated at $8\,h^{-1}$ kpc and possesses a core radius of $0.065\,h^{-1}$ kpc. ($\Omega = 1$ and $\Lambda = 0$ are assumed throughout.) The rotation velocity of the disc is $200\,\mathrm{km\,s^{-1}}$. Fig. 2 presents the source and image planes for this model, with the elliptical and diamond caustic, and corresponding critical lines, apparent. In this model, the quasar images are not substantially magnified, with a total magnification of ~7, and with the intrinsic source of APM 08279+5255 being correspondingly luminous, $L_{\mathrm{bol}} \sim 7 \times 10^{14}\,\mathrm{L}_{\odot}$. While extreme, this value is not necessarily outrageous as the unlensed quasar HD 1946+7658 possesses an intrinsic luminosity of $\sim 4 \times 10^{14}\,\mathrm{L}_{\odot}$ (Hagen et al. 1992), and APM 08279+5255 may be a member of this very luminous class of quasars. It must be conceded, however, that the non-uniqueness of the lens model translates into uncertainty in the model magnification, and a true determination of the intrinsic properties of APM 08279+5255 requires models derived from better observational constraints.

The CO source is taken to have a circular surface brightness

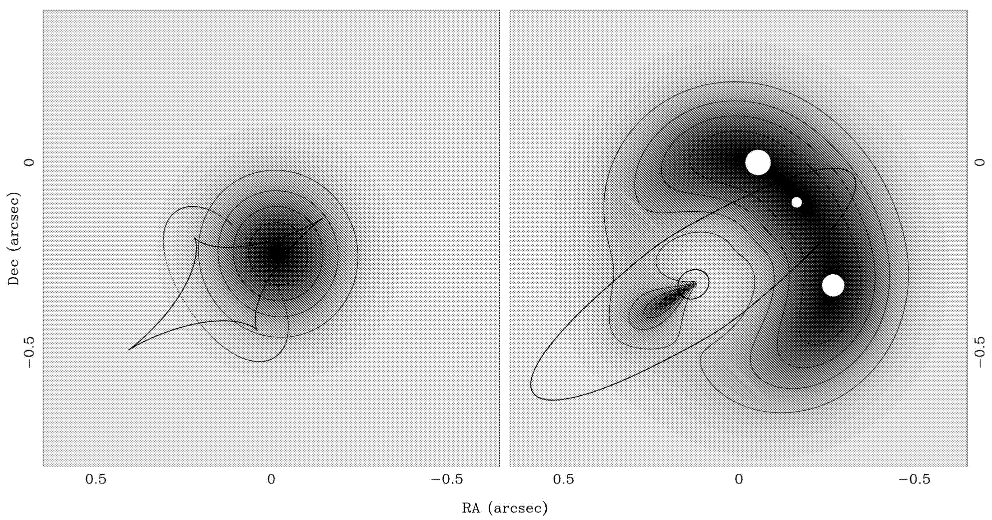

Figure 2. The source plane (left) and image plane (right) for the gravitational lens model for APM 08279+5255. The diamond and elliptical caustics, and their corresponding critical lines, are apparent in the panels. The contour lines represent the CO source and image and the solid circles represent the positions and brightnesses of the quasar images as determined from the *HST* images (Ibata et al. 1999). Note, however, that the model presented in the paper results in brightness ratios of C ~ B ~ 0.75 A, whereas the observed ratios are C ~ 0.2 A and B ~ 0.8 A.

distribution centred upon the quasar position. One important aspect of the results presented herein is that APM 08279+5255 becomes the second system for which the gravitational lens can be used to study structure on sub-kiloparsec scales in the molecular gas associated with the AGN host galaxy, the first system being the Clover Leaf quasar, H1413+117 (Yun et al. 1997; Kneib, Alloin & Pello 1998). For APM 08279+5255, the observations and lens model require the CO to be distributed on a scale covering a substantial fraction of the caustics in the image plane, but not so large as to lose the ring structure. The lower limit to the CO source size based on the modelling is $\sim 400\,h^{-1}$ pc, while a rough upper limit is ~ 1 kpc. With this model, the CO(1–0) has been magnified by a factor of ~ 2.5–3. Like the Clover Leaf, we find that the spatial extent and mass of the molecular gas in APM 08279+5255 are comparable to those seen in nearby nuclear starburst galaxies (Sanders & Mirabel 1996; Downes & Solomon 1998).

Downes et al. (1999) determined a CO source size of $\sim$(80–135) h^{-1} pc for the estimated magnification factors of ~ 20–7. This size is much smaller than the one calculated above, while their magnification factors are larger. Their analysis is based upon modelling of CO emission in the gravitationally lensed ultra-luminous galaxy *IRAS* F10214+4724 (Downes, Solomon & Radford 1995), the image of which is clearly an extended arc-like feature which possesses an essentially linear magnification. Such a simple model is probably a poor representation of the lensing in APM 08279+5255. Additionally, Downes et al. (1999) assumed that the velocity filling factor is unity, substantially larger than the value derived in Section 2, as the intrinsic source radius in their model scales inversely with this value and the magnification factor is proportional to it. For $f \sim 0.35$, a value well within our estimated range, the Downes et al. (1999) model yields an upper limit for the intrinsic source size and a lower limit for the magnification factor that are similar to ours.

Accounting for the influence of gravitational lensing, the velocity-integrated CO(1–0) flux density implies that the nuclear content of molecular gas in APM 08279+5255 is $\sim 10^{10}\,h^{-2}\,M_\odot$, assuming a CO-to-$H_2$ conversion factor of $\sim 1(M_\odot\,km\,s^{-1}\,pc^2)^{-1}$ which is typical for starburst/kinematically violent, ultraviolet-intense environments of gas-rich, infrared-ultraluminous systems (Downes & Solomon 1998). Assuming that the CO is in a rotating disc, the dynamical mass can be calculated from the radius of ~ 500 pc set by the lens modelling, and using a rotational velocity of 350 km s^{-1} set by the observed line velocity HWHM = 250 km s^{-1} and assuming a disc inclination angle of 45° (Downes et al. 1999). The implied dynamical mass is $1.5 \times 10^{10}\,M_\odot$ within ~ 500 pc of the nucleus, consistent with the value derived from the CO flux. Hence it appears likely that the molecular gas mass makes a significant, and perhaps dominant, contribution to the total mass within a few hundred parsecs of the nucleus in APM 08279+5255, unless the nuclear CO disc is close to face-on. A similar conclusion has been reached for most nearby nuclear starburst galaxies (Downes & Solomon 1998).

4 CONCLUSIONS

This paper has presented resolved images of nuclear CO(1–0) emission in the gravitationally lensed broad absorption line quasar APM 08279+5255. While the continuum emission is found to be well aligned with the optical quasar images, the CO(1–0) is more extended, with a broken ring-like appearance. Such a structure is consistent with the action of gravitational lensing, with the continuum emission occurring on the scale of the quasar core, while the CO(1–0) arises from a larger region and is differentially magnified. The three-image nature of APM 08279+5255 has posed a problem for lens modelling, as an extremely large, flat core is required to produce the central image. Such three-image configurations are a natural consequence of gravitational lensing by a flattened potential which can produce naked cusps. Modelling of the CO(1–0) emission supports this hypothesis, although a deficit in constraints implies that the model is not unique. An immediate prediction of this model is that the lensing galaxy, the position of which could be revealed by observing below the Lyman limit for this system ($\lesssim 4400$ Å), hence removing the glare from the quasars, should be offset ~ 0.5 arcsec from the quasar image, rather than lying directly in front of them.

Currently, our CO images of APM 08279+5255 are of limited signal-to-noise ratio. However, with further integration a detailed map of the CO image can be made. As this region will be free from the effects of microlensing, and as its extended nature provides many more constraints (Kochanek et al. 2001), such imaging has the potential to provide a more accurate model of the lensing in APM 08279+5255 than from the quasar images.

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