Disturbed neutral hydrogen in the galaxy NGC3067 pointing to the quasar 3C232

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THE quasar-galaxy pair 3C232 and NGC3067 was the first in which Ca II absorption was found in the higher redshift spectrum of the quasar at the lower redshift of the galaxy[1]. This has been taken as evidence that quasar absorption lines are due to gas associated with extended disks or spherical haloes of galaxies distributed along the line of sight[2]. Implicit in this is the assumption that redshifts are cosmological. We present new observations of neutral hydrogen at the redshift of NGC3067, both in emission and absorption against the radio-loud quasar. The hydrogen forms a long tail, apparently extending from the galaxy to the quasar and beyond, which seems to be a disturbed extension of one of the galaxy's spiral arms. No companion to NGC3067, which might cause such a disturbance, can be seen. The extended gas distribution, mapped here for the first time in such a system, conforms neither to the extended disk, nor to the spherical halo model. We suggest that most low redshift absorption line systems arise in extended gas associated with interacting galaxies unless, of course, our line-of-sight passes through the optical disk of the associated galaxy.

The optical field for this pair is shown in Fig. 1. The redshift of the quasar is 0.5303, which implies a luminosity distance of 2,760 Mpc (we assume $H_0 = 50$ km s^{-1} Mpc^{-1}, and $q_0 = 1/2$). The galaxy redshift is 0.0049 (which corresponds to a velocity of 1,456 km s^{-1}), giving a distance of 29 Mpc[1,3]. Notice the prominent dust lanes in the eastern half of the galaxy. The galaxy has been classified as Sc (dust)[4]. Radio spectra of the quasar[3,5] reveal H I 21 cm absorption at a heliocentric velocity of 1,420 km s^{-1}, with a full-width half-maximum of 3.75 km s^{-1}; optical spectra (J.T.S., manuscript in preparation) show three heavy-element absorption line systems at 1,371, 1,417 and 1,545 km s^{-1}, with widths $\leq$15 km s^{-1}. The angular separation of the pair projects to 16 kpc at the redshift of the galaxy. This would be the minimum halo radius if the absorbing gas is halo material. If the absorption were by gas in a flat disk, then the disk radius must be at least 60 kpc, and the rotation velocity at 60 kpc would be twice as high as at the edge of the optical disk of the galaxy[3].

We made observations on 19 April 1988 for 8 hours in the C configuration of the Very Large Array (ref. 6). Sixty-three spectral channels were used, with a velocity resolution of 20.8 km s^{-1}, centred at 1,456 km s^{-1} (heliocentric for the 21-cm line) and we used amplitude and phase self-calibration. The quasar continuum was removed according to the guidelines set out in ref. 7. A spectrum of the quasar showed a residual ripple in the band pass with an r.m.s. of 1.6 mJy per beam per channel (about 0.1% of the flux of 3C232). This ripple is large enough to confuse any real emission below about 3 mJy per beam within 10″ of the quasar in each spectral channel image.

The systemic velocity for the H I emission from NGC3067 is 1,465 ± 10 km s^{-1}, as calculated from the integrated H I profile, the position velocity profile along the galaxy major axis, and the isovelocity contours. The kinematic centre for the H I is at RA = 09 h 55 min 25.6 s, dec. = 32°36′33″ (1950; Fig. 2). Hence, the kinematic centre for NGC3067 is displaced from the optical centre by 10″ to the west, and from the radio continuum centre by 6″, again to the west. The galaxy's gaseous disk seems to be truncated in the west just beyond the point where the rotation curve becomes flat. The position-velocity profile along the galaxy major axis (Fig. 3) shows this asymmetry clearly, with the receding side of the disk (east) extending almost twice as far as the approaching side (west).

The most striking feature on our images is the long 'tail' of H I emission extending towards and over the quasar (Fig. 2). The full length of the tail is about 3′, or 24 kpc at the redshift of the NGC3067, and the deconvolved width is about 17″, or 2.3 kpc. The H I distribution in the velocity range from 1,332 to 1,600 km s^{-1} in the tail is probably gas that has been pulled away from the northern spiral arm of NGC3067. This explains why a rather extended H I disk can be seen south of the galaxy, with no corresponding feature in the north.

Just north of the quasar, the H I emission goes through a minimum and then terminates further to the northeast in a cloud which has a velocity dispersion covering almost the entire velocity range of the galaxy. This emission is suspect because the cloud sits quite closely to the peak sidelobe from 3C232 (about 8% of the peak). If this emission is real, we see an interesting trend for velocity width along the tail. The width of the emission profile increases steadily from 30 km s^{-1} in the southwest to 200 km s^{-1} in the northeast. Although they are admittedly unreliable, our data at the position of 3C232 fit in quite well with this trend. Other evidence for a large velocity dispersion at

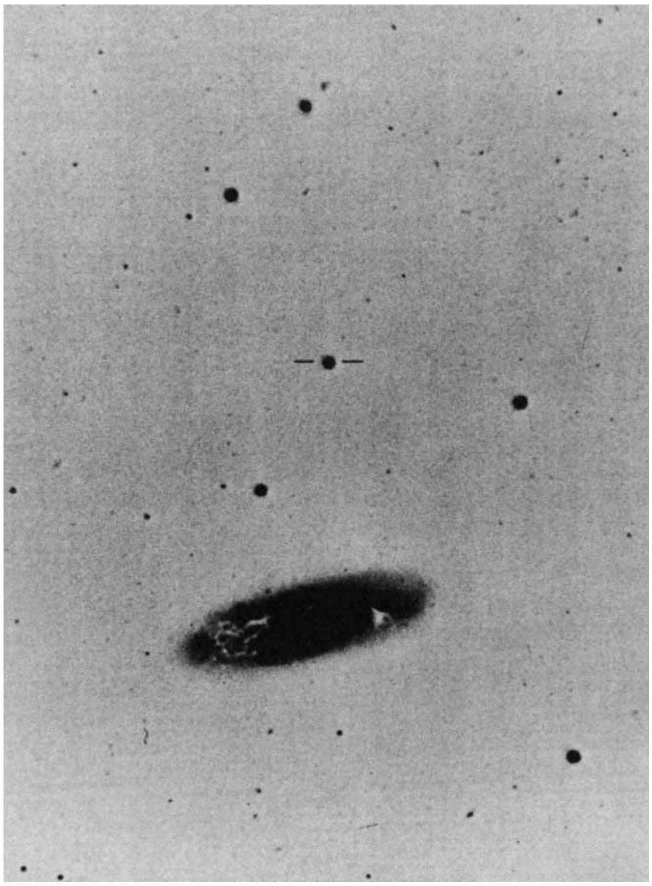

FIG. 1 The optical field of the quasar galaxy pair 3C232–NGC3067 (from a blue plate taken with the Kitt Peak National Observatory 4-m telescope, kindly supplied to us by Dr H. C. Arp). The quasar sits 2′ north of the galaxy, and is marked with bars running east–west. The optical radius of the galaxy is $R_{25} = 74''$, and the galaxy is inclined at an angle of 75° (ref. 3). The quasar has a continuum radio flux at 1,414 MHz of 1.33 Jy. The integrated continuum flux from NGC3067 is 54 mJy, which implies NGC3067 is probably a starburst galaxy. This assertion is supported by the high 60 μm and 100 μm Infrared Astronomical Satellite fluxes for NGC3067 (9.0 and 18.5 Jy respectively; H. C. Arp, personal communication).

3C232 is the fact that optical absorption occurs over a velocity range of 170 km s^{-1}. Note that large velocity dispersions (>100 km s^{-1}) are often seen in high-redshift ($z > 0.5$) metal-line-absorption systems, while low-redshift systems ($z < 0.1$) typically have small dispersions (<50 km s^{-1})[8].

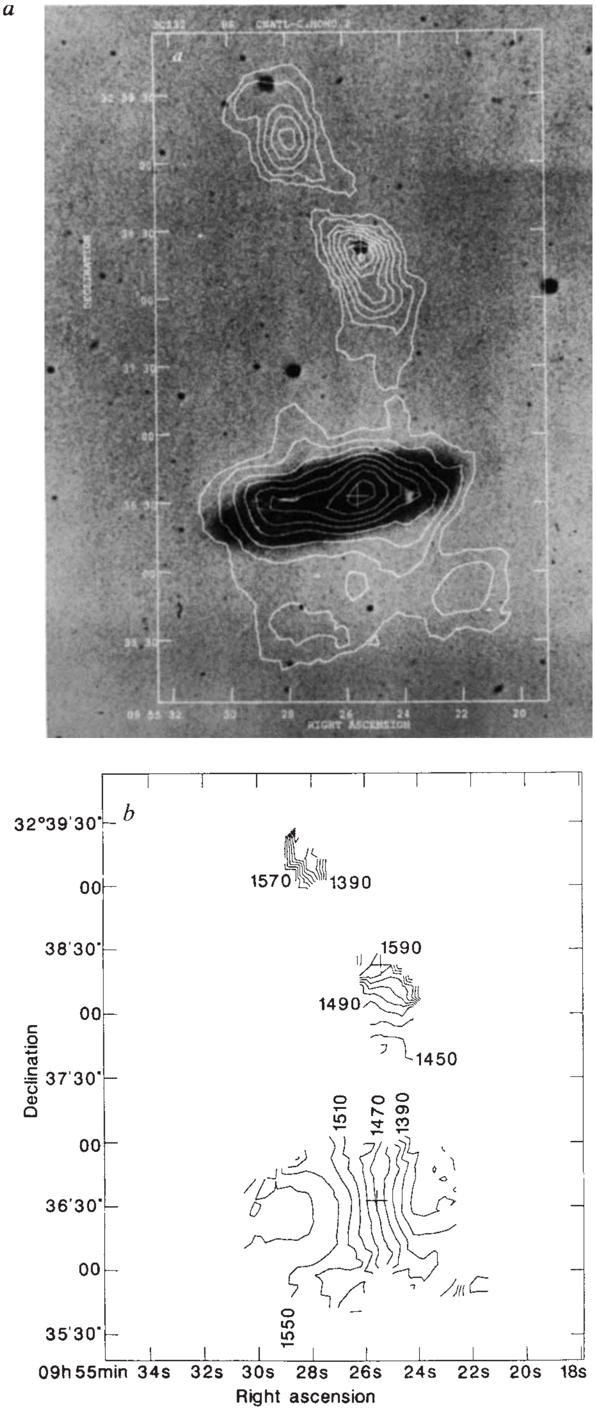

FIG. 2 *a*, The integrated neutral hydrogen emission from NGC3067 (the H I column density and the optical field). Contour levels are: 2.9, 5.9, 10.3, 14.7, 19.2, 23.6, 28.0 and 32.4, $\times 10^{20}$ atoms cm^{-2}. *b*, The H I intensity weighted mean velocity field. Contours are spaced by 20 km s^{-1}, starting at 1,370 km s^{-1}. Crosses mark the quasar and galaxy kinematic centre positions. Notice the systematic deviations from circular motions in the north and south in the isovelocity contours. This is caused by the spiral arms, which are seen in the optical image at these positions. In the east the opening angle of the contours decreases, indicating a flattening of the rotation curve. The peak rotational velocity is 160 km s^{-1}. In the west, the position angle of the line of nodes changes dramatically in the outer part, confirming the idea that the galaxy is severely warped in the west.

We assume that the heavy-element absorbing gas is associated with the H I observed in emission. This implies that the absorbing gas associated with NGC3067 towards 3C232 is neither in an extended disk nor a halo, but in a long 'tail' of H I, extending well beyond the galaxy's optical disk. This result is not surprising for a number of reasons. First, observations of 21-cm emission from nearby spirals show that relatively isolated galaxies with regular H I disks rarely show H I extending beyond two Holmberg radii. Recent observations (ref. 9; R. Sancisi, J.H.v.G., T. Cornwell and J. v. Albada, manuscript in preparation) show that for most galaxies, the H I cuts off very sharply near the optical radius of the galaxy, at column densities of 10^{19} cm^{-2}. Second, when very extended H I is observed, it is usually in interacting pairs or groups of galaxies (compare the Leo triplet, M51, Mk 348 and most recently Arp 143; refs 10–12). Lastly, from optical absorption studies, Morton *et al.*[13] propose a sharp cutoff for Ca II and Mg II at about the optical radius of a galaxy, although 'the presence of a Magellanic Stream in the halo could increase this distance'. When we review their sources, we find that for every system in their study with known Ca II absorbing gas outside the associated galaxy's optical radius, the galaxy shows evidence that it is involved in an interaction.

Therefore we conclude that the most likely origin for the low-redshift-absorption-line systems (the Ca II systems), is extended gas in interacting systems, unless of course our line-of-sight to a quasar passes through the optical disk of a foreground spiral.

How does our conclusion concerning the low-redshift systems affect our understanding of the origin of the higher redshift quasar-absorption-line systems? Unfortunately, the relationship between the low-redshift systems ($z_{abs} \leq 0.1$) and the higher redshift systems ($z_{abs} \geq 0.5$) remains uncertain. On the other hand, systems such as NGC3067 have often been cited as evidence for extended gaseous haloes or disks around galaxies. Our observation shows that this assumption is incorrect. Clearly then, using such systems to support the idea that the high redshift absorption line systems arise in galaxy haloes is also incorrect.

It is clear that NGC3067 has been severely disturbed. This is evident from its optical appearance, its very asymmetric gas distribution, and the presence of the H I tail. We now turn to the question of what object caused this disturbance. The problem is that NGC3067 has no obvious optical companions. An inspection of the Palomar Sky Survey shows a compact galaxy MRK412 about 10′ south of NGC3067. But this galaxy has a

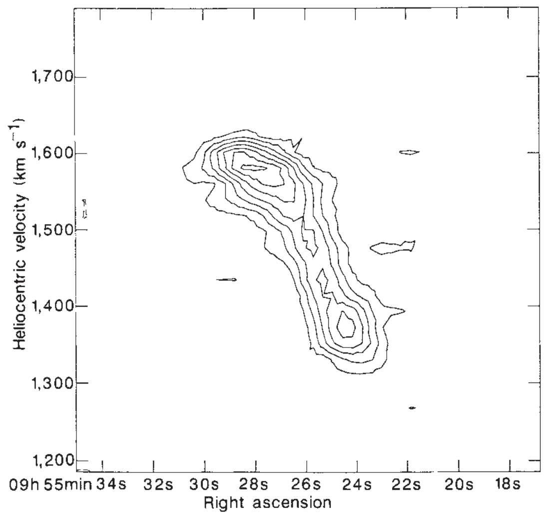

FIG. 3 A position-velocity plot along the major axis of NGC3067 (p.a., 101.5°). Notice how the rotation curve flattens in the east at ~1,600 km s^{-1} and extends about 70″ from the galaxy kinematic centre. In the west the emission terminates just where the flat rotation curve should begin. The truncated disk in the west is also obvious in optical slit spectra along the galaxy major axis[3].

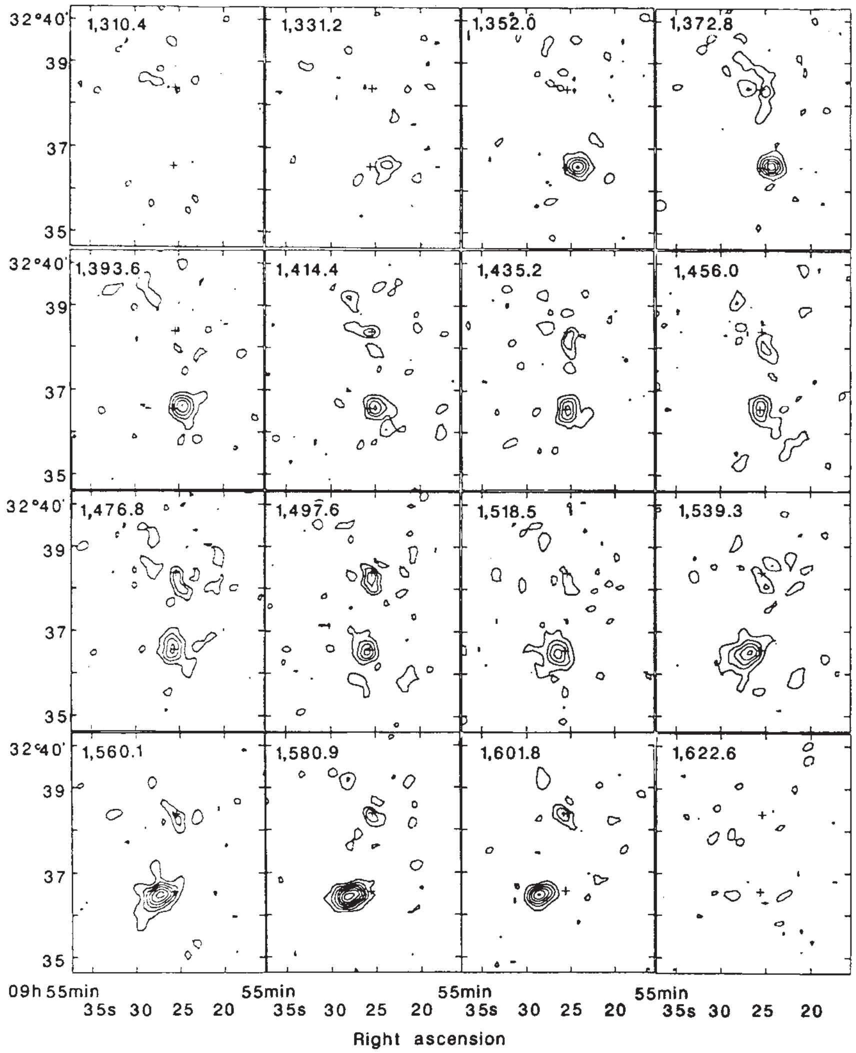

FIG. 4 The central 16 spectral line channels. This covers the entire velocity range of the galaxy (1,300 to 1,620 km s^{-1}). Crosses mark the position of the quasar and galaxy centre. The noise per channel on the natural weighted images was 0.6 mJy per beam, or 1.1 K. The heliocentric channel velocity for the H I is indicated above each image. The contour levels are: −4.5, −3.0, −1.5, 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 12.0, 13.5 mJy per beam. The full-width half-maximum of the gaussian restoring beam after CLEANING was 19″ for the natural weighted images. Notice how the tail first appears close to the quasar at 1,372 km s^{-1}. Then at 1,414 km s^{-1} it is seen in absorption against 3C232, and in emission to the northeast and southwest of the quasar. At 1,432 and 1,456 km s^{-1} it comes up more strongly close to the galaxy. Images at lower resolution show the tail connecting to the galaxy in this velocity range. With increasing velocity, the tail extends to the northeast while the galaxy's emission moves to the southeast. It can be seen close to 3C232 at velocities as high as 1,600 km s^{-1}. Notice how well the tail fits in with the velocity field of the galaxy. In fact, inclusion of the tail in the integrated H I spectrum of NGC3067 removes the pronounced asymmetry in velocity that was first noticed by Rubin *et al.*[3]. Both these facts support the conclusion that the tail is H I gas associated with NGC3067.

redshift three times larger than NGC3067 (ref. 14). MRK411 has a redshift similar to NGC3067, but it sits 75′ north, which projects to about 0.6 Mpc at the galaxy redshift. There is also a small spiral galaxy 15′ northeast of NGC3067, although its distance is unknown. It is most likely that the disturbing mass has been cannibalized by NGC3067. This conclusion is supported by the appearance of a multiple optical nucleus in the images presented by Burbidge *et al.*[15]. Also, the unusually strong radio continuum and infrared luminosities of NGC3067 place it in the starburst class of galaxies, which are currently thought to be mergers.

We conclude with a brief discussion of the implications this system has on our understanding of quasar redshifts. The position of the quasar in this tail may be a coincidence of projection. We have the additional coincidence that the velocity dispersion at the quasar seems to be considerably larger than that in the tail to the south of the quasar. This is evidenced both by the radio H I emission studies and by the optical absorption studies (although we have mentioned potential problems with the radio data at the quasar position). Radio observations with improved band-pass calibration would be extremely useful in clarifying the velocity field in the vicinity of the quasar.

Although reminiscent of the optical examples of tails pointing to quasars[16], an important difference is that this tail is hydrogen-rich, which allows us to calculate the effects the quasar would have on the ambient material if it were local to the tail. From our 21-cm observations, and from extrapolation to shorter wavelengths of the International Ultraviolet Explorer spectra of 3C232, we calculate a radius of 1.8 kpc for the H II region induced by the quasar. This is slightly larger than the tail radius. The expected emission measure from such a region is 190 pc cm^{-6}, which is just below the sky survey limit. One can easily go deeper than the sky survey with even short exposures on metre class telescopes. If no emission is observed, then stringent limits can be set on the quasar-tail distance. □

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