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NGC 3628: Ejection Activity Associated with Quasars

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Abstract. NGC 3628 is a well-studied starburst/low level AGN galaxy in the Leo Triplet noted for its extensive outgassed plumes of neutral hydrogen. QSOs are shown to be concentrated around NGC 3628 and aligned with the HI plumes. The closest high redshift quasar has z=2.15 and *is at the tip of an X–ray filament emerging along the minor axis HI plume.* Location at this point has an accidental probability of $\sim 2 \times 10^{-4}$. In addition *a coincident chain of optical objects coming out along the minor axis ends on this quasar.*
More recent measures on a pair of strong X–ray sources situated at 3.2 and 5.4 arcmin on either side of NGC 3628 along its minor axis, reveal that they have nearly identical redshifts of z=0.995 and 0.981. *The closer quasar lies directly in the same X–ray filament which extends from the nucleus out 4.1 arcmin to end on the quasar of z=2.15.*
The chain of objects SW along the minor axis of NGC 3628 has been imaged in four colors with the VLT. Images and spectra of individual objects within the filament are reported. It is suggested that material in various physical states and differing intrinsic redshifts is ejected out along the minor axis of this active, disturbed galaxy.

Key words. galaxies: active - galaxies: individual (NGC 3628) - quasars: general - Radio sources: 21 cm radiation - galaxies: X–rays

1. Introduction

NGC 3628 (z=0.0028) is a nearby, edge-on Sbc peculiar galaxy which is undergoing major internal dynamic activity that is, however, shrouded from our view by a prominent dust lane. See Atlas of Peculiar Galaxies No. 317 (Arp 1966). For a comprehensive summary of the galaxy parameters and current observational status, see Cole, Mundell and Pedlar (1998). For a discussion of a possible AGN within NGC 3628, see Yaqoob et al (1995).

A prominent feature of NGC 3628 is the long HI plumes being outgassed from the galaxy in two directions. The major plume to the ENE was best imaged by Kormendy and Bahcall (1974) as a long, straight optical jet. Later it was observed in HI with the Arecibo telescope by Haynes, Giovanelli and Roberts (1979) who also mapped a weaker plume towards the south along the minor axis. The usual explanation for the plume morphology is that it is due to a tidal encounter between NGC 3628 and the nearby similar-sized spiral NGC 3627, although the velocity profile and substructure of the plume caused Haynes et al. to comment that "...the observational data somewhat strain the model parameters." It could also have been noted that comparable HI extensions were not drawn out of adjoining galaxies with which NGC 3628 was supposed to have interacted.

Haynes et al.'s definitive mapping of the plume morphology is replicated here in Fig. 1, minus the complete extension to the ENE, and without the 3K km s^{-1} contour about which Haynes et al. counselled caution. The velocity profile of the strongest plume is that of steady flow velocity away from the galaxy out to beyond the left edge of Fig. 1.

This extended hydrogen is originating from the central regions of NGC 3628, either from starburst activity or from a dust-enshrouded AGN. Fabbiano, Heckman and Keel (1990) concluded that the X-ray observations demonstrated "... collimated outflow from a starburst nucleus...", and Irwin and Sofue (1996) found expanding molecular shells of CO emanating from the nucleus. NGC 3628 is known to have a strong X-ray source in its core, and, unusually, a second strong X-ray source toward the east end of its disk. Previous work by Radecke (1997), Arp (1997, 1998) and others has shown a 7.4 sigma association of

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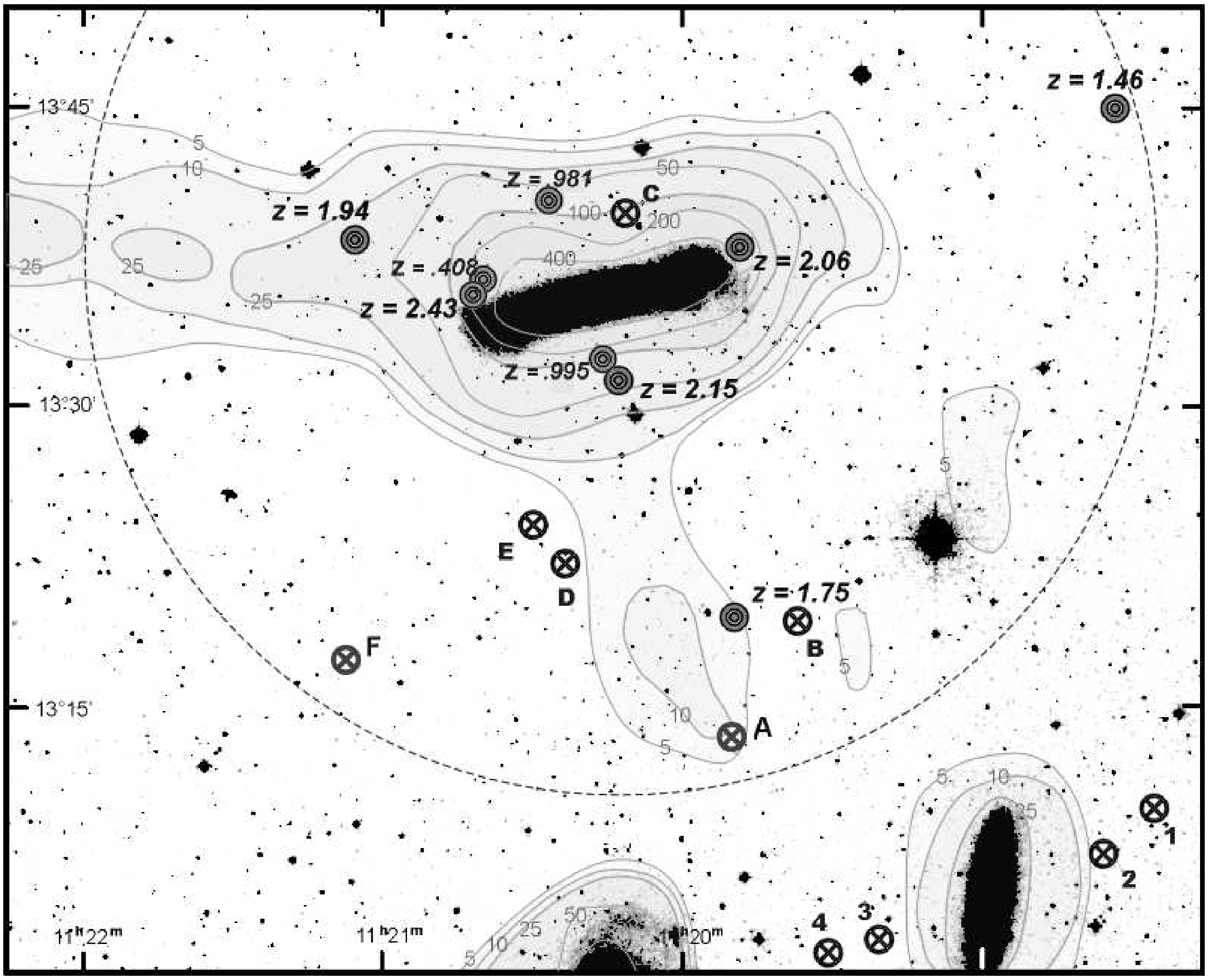

Fig. 1. Isophotal contours of neutral hydrogen (HI) are shown coming from the starburst/AGN galaxy NGC 3628 (from Haynes, Giovanelli and Roberts (1979). Catalogued quasars from Weedman (1985) and Dahlem (1996) are annotated with their redshift values. The search field of Weedman is bounded by the dashed line. Objects marked with a circled X are probable quasars plus F, a possible quasar. (see Tab. 1 for detailed data).

quasars with Seyfert galaxies, which we have attributed to ejection from their active nuclei. Since NGC 3628 is a prominent nearby galaxy which is so clearly seen to be expelling material from an active nucleus, we looked to see if there are quasars close to this galaxy. As can be seen in Fig. 1, there are indeed known quasars in the near vicinity of NGC 3628, even in near **proximity** to its active disk. In this paper we will discuss evidence that these quasars are being ejected from NGC 3628 along with the HI gas and X-ray material.

2. Quasars and candidates near NGC 3628

Dahlem et al (1996) have listed many X-ray emitting sources in the ROSAT-detected hot gaseous halo of NGC 3628. They found that this density of sources was over twice that of the wider background (=1.5 sigma deviation), but made no firm statistical statement because only small numbers were involved. Dahlem et al. note that the emission properties of these sources point to their identification as either AGN (QSOs) or X-ray binaries. Since it is unlikely that powerful binary sources are present in the halo it is much more probable that these sources are more closely related to AGNs. In the standard model these QSOs would be assumed to be background objects, their greater density near NGC 3628 notwithstanding. In the alternative model advanced by Arp (1987), G.R. Burbidge and others, most of these QSOs are associated with NGC 3628, as is the case for other galaxies with physically associated quasars, see e.g., E.M. Burbidge (1999).

Fig. 1 shows 15 confirmed or probable QSOs in the surveyed area, of which 10 are within the galaxy's plume contours. The average background density which Weedman (1985) found for his 20 CFHT grism fields was 10/sq. deg. for $2.0 \leq z < 2.5$ to $m_{4500} = 21$ mag. For $1.75 \leq z < 2.5$ the density rises to 13.9/sq deg +8/-6 and this background density is plotted in Fig. 2.

Table 1. Objects in Fig. 1.

Obj	Survey ID	Prob. QSO	R.A. (J2000)	Decl	E	O	Notes
z=1.46	Wee 47	QSO	11 18 30.3	13 45 01	18.5	18.9	No X-ray
z=2.06	Wee 48	QSO	11 19 46.9	13 37 59	19.2	20.0	2RXP 6 cts/hr
z=1.75	Wee 50	QSO	11 19 48.2	13 19 38	19.3	19.8	No X-ray
z=2.15	Wee 51	QSO	11 20 11.9	13 31 23	19.4	19.6	1RXH 5 cts/hr
z=0.995	1WGAJ1120.2+1332	QSO	11 20 14.7	13 32 28	19.5	20.7	1RXH 3 cts/hr
z=0.981	1WGAJ1120.4+1340	QSO	11 20 26.2	13 40 24	18.6	19.8	1RXH 9 cts/hr
z=0.408	1WGAJ1120.6+1336	QSO	11 20 39.9	13 36 20	19.1	20.1	1RXH 3 cts/hr
z=2.43	Wee 52	QSO	11 20 41.6	13 35 51	19.5	20.3	1RXH 3 cts/hr
z=1.94	Wee 55	QSO	11 21 06.1	13 38 25	18.0	18.7	2RXP 22 cts/hr
A	Wee 49	Probable	11 19 48.3	13 13 30	19.9	20.6	Two EM lines
B	2RXPJ111935.0+131921	90%	11 19 35.1	13 19 24	18.6	19.6	7 cts/hr
C	1RXHJ112010.3+133939	74%	11 20 10.5	13 39 34	18.8	21.0	16 cts/hr
D	2RXPJ112022.6+132212	97%	11 20 22.8	13 21 58	19.8	20.4	9 cts/hr
E	2RXPJ112028.8+132416	85%	11 20 29.4	13 23 57	19.7	20.4	14 cts/hr
F	Wee 56	Possible	11 21 09.7	13 17 53	19.9	20.9	One EM line
1	1RXHJ111821.9+130957	71%	11 18 21.7	13 09 57	-	21.0	2 cts/hr
2	1RXHJ111832.6+130732	100%	11 18 32.5	13 07 32	19.1	20.0	6 cts/hr
3	1RXHJ111919.1+130315	85%	11 19 18.9	13 03 17	19.8	20.6	5 cts/hr
4	1RXHJ111928.8+130249	99%	11 19 28.4	13 02 51	17.6	18.4	12 cts/hr

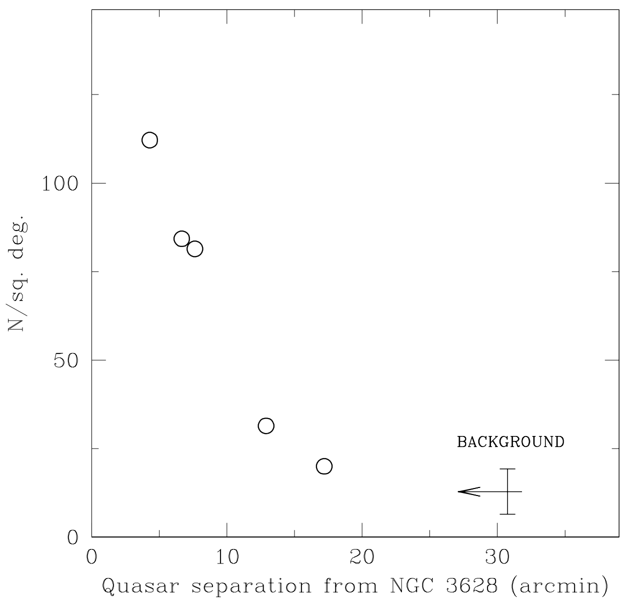

Fig. 2. The density of Weedman catalogued quasars at the distance of each quasar from NGC 3628 is plotted. The arrow marks the upper limit to average background density of 1.75 $\leq z \leq$ 2.5 quasars. The area blocked by NGC 3628 has been excluded.

It is seen that the closest Weedman quasars to NGC 3628 reach a density of about 100/sq. deg. The chance of finding the two closest quasars at 19.7 and 19.9 mag. is only 0.002 (using Poisson statistics). Of the three closest, the QSO with z=2.43 is 21.2 mag., probably fainter due to absorption by the galaxy, but still making the probability of chance concentration even smaller. This probability is an upper limit because the background counts are over estimated. This is due to the fact that, as we have seen, the Weedman survey inadvertently pointed near some very active galaxies and then only used counts from plates which showed the most quasars below m_{4500} = 20 mag.

Tab. 1 summarizes what is known about the quasars and quasar candidates depicted in Fig. 1. In Tab. 1 confidence values that these objects are QSOs are displayed as percentages. These are taken from the whole–sky X-ray/radio/optical overlays catalogue by Flesch, which is accessible at ftp://quasars.org/quasars (paper in preparation).

Briefly, the method is to first calculate likelihoods of X-ray-optical association for each cross-category of X-ray-optical offset distance, optical PSF, and O-E color, by comparing the found density of such optical objects to the whole-sky background density of such objects, using a 650,000,000-object merge of the APM and USNO optical catalogues, subcategorized by local sky densities to minimise local effects. These likelihoods are then used to realign the astrometry of the ROSAT X-ray fields with the optical background, then the likelihoods are recalculated, and this process is iterated to stability. Having thus obtained best X-ray-optical positional fits, the most likely optical object is determined for each X-ray detection, and where there is a good optical candidate, the probability that it is a QSO is derived from the numerical prevalence of known QSOs/galaxies/stars having that object's X-ray-optical positional offset, PSF, O-E color, and X-ray-to-optical flux ratio, decreased by the calculated probability that the X–ray association is false. A fuller accounting is

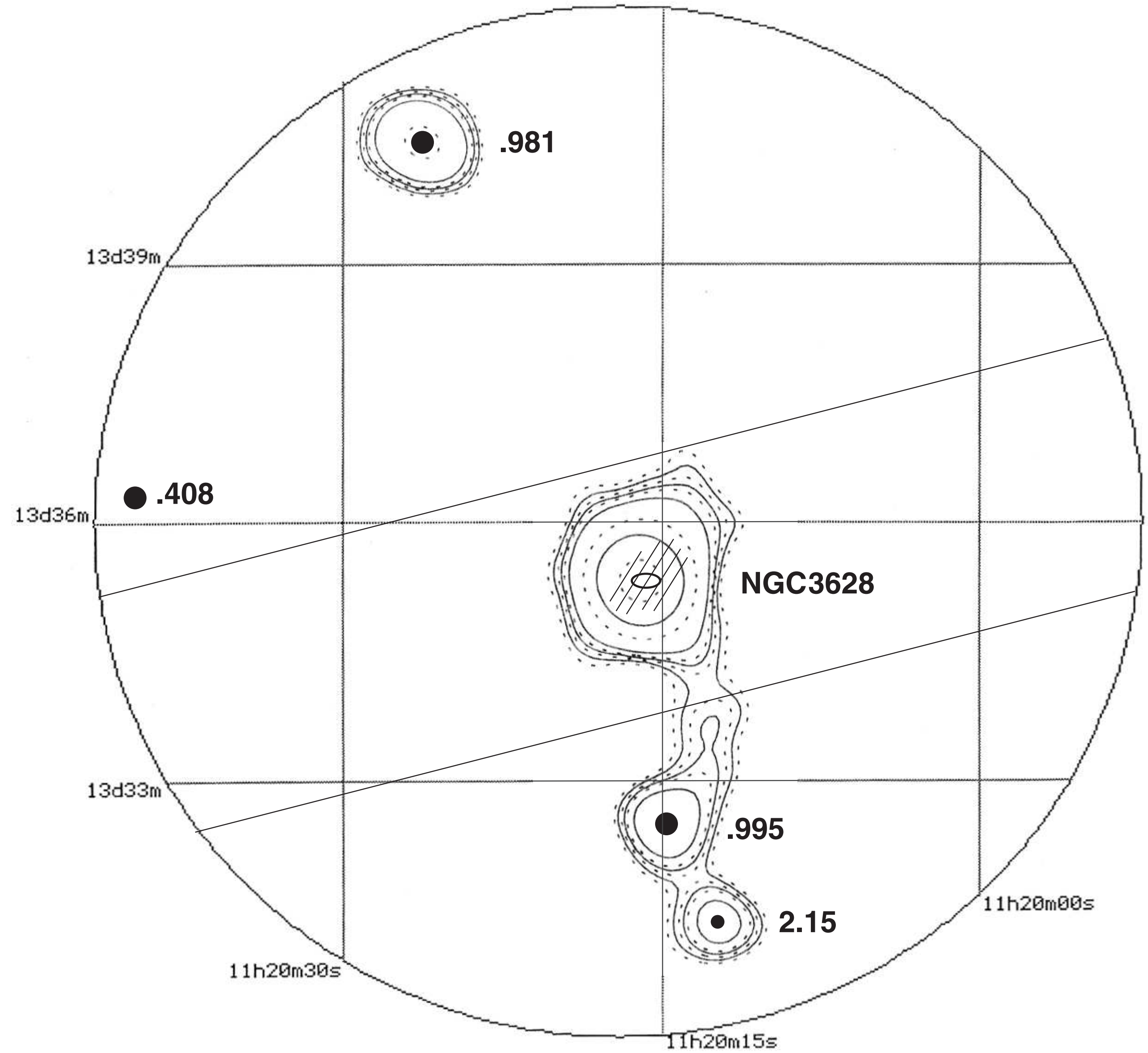

Fig. 3. The broad band (0.1 to 2.4 keV) ROSAT map of NGC 3628 smoothed and contoured from PSPC photon event files. It is quite similar to the map presented by Dahlem et al. (1996). The optical position of the X-ray quasars in the field, however, have now been indicated as filled circles with their redshifts labelled.

provided by the readme which accompanies the catalogue at the web address.

Tab. 1 also lists four X-ray quasar candidates around NGC 3623. Fig. 1 shows that NGC 3623, an adjoining bright member of the Leo Triplet, has these four probable quasars aligned across its nucleus, two on either side. Redshifts of these candidates would furnish additional confirmation of ejection of quasars from these Leo Group galaxies.

3. Quasars in the galactic disk of NGC 3628

In Fig. 1 the z=2.43 quasar is the X-ray source Dahlem #16. Only 37 arcsec away is the X-ray source Dahlem #15 which we have identified with a blue stellar object (BSO) of similar apparent magnitude. RIXOS (Strickland et al. 2000) measures reported z=0.408 for the second component of this apparent double quasar. Optical identification of these objects was enabled from the coordinates of Read et al. (1997) and interchange of the published declinations of Dahlem #15 and #16 (M. Dahlem, private communication).

The quasars at both the east and west end of the disk appear to be associated with strong disturbances in NGC 3628 at these points. Luminous features and dust features point in the general direction of the quasars and there are hints of filaments and perturbations which, when explored with deeper, higher resolution images from larger telescopes, may link these quasars with the general eruption of material in these regions.

4. Quasars in the HI Plumes

Fig. 1 shows alignment between the HI plumes of NGC 3628 and nearby quasars. Quasars with z=1.94, 2.43 and 0.408 lie at the base of the main ENE plume, coincident with the start of the optical jet imaged by Kormendy and Bahcall (1974). Two more, with z=2.06 and 1.46, align in roughly the opposite direction. Four more lie in the southern plume, z=0.995, 2.15. 1.75 and candidate A (Wee 49). The latter two lie along a thickening of the plume. The probable quasar Wee 49 lies, very interestingly, right at the tip of the southern HI plume. Thus these quasars are not only aligned with the plumes, but positioned along contour nodes. This is strongly indicative of physical association, and implies that these quasars and HI plumes have come out of NGC 3628 in the same physical process.

5. X-ray Ejection from the Nucleus of NGC 3628

As referenced previously, the first X-ray observations established collimated outflow along the minor axis of NGC 3628. The later ROSAT observations confirmed this result and established narrow filaments and point sources extending outward from the nucleus (Dahlem et al, 1996; Read, Ponman and Strickland 1997). Fig. 3 here, the best resolution PSPC X-ray map, shows a narrow jet/filament coming from the bright X-ray nucleus continuously out to end at the z=2.15 quasar.

The X-ray contours shown in Fig. 3 were processed from ROSAT photon event files by Arp. The resultant X-ray maps in both broad band (shown in Fig. 3) and hard band show essentially the same connection from the nucleus of NGC 3628 to the z=2.15 quasar that the maps of Dahlem et al. (1996) show.

If we adopt the last X-ray source as the end of the filament, then the quasar falls essentially at its tip. The accuracy of the superposition is obtained by taking the X-ray position of Dahl#7 and differencing it with that of the APM position of the quasar. That yields a displacement of ∼20 arcsec and a probability of accidental superposition of $\sim 10^{-3}$. However, identifying optically the stronger Dahlem sources gives ∼12 arcsec systematic correction for the X-ray positions. That yields a coincidence of 8 arcsec, about the accuracy of PSPC identifications, and a probability of accidental coincidence of 2×10^{-4}.

This quasar, as marked in Fig. 3, is an X-ray source and the next source in toward the nucleus also is a point X-ray source which has been measured by RIXOS at z=0.995.

6. The Pair

At a slightly greater distance on the other side of the NGC 3628 nucleus, along the N minor axis, is a brighter X-ray source which is identified with an E = 18.6 mag., blue stellar object (BSO), shown as object C in Fig. 1. This was observed to be a quasar of z=0.984 by E.M Burbidge in 1999:

Line	λ_{obs}	z
Mg II 2800	5565	0.988
CIII] 1909	3780	0.980

Later RIXOS (Mason et al. 2000) reported for the same two lines a redshift of z=0.977. We adopt z=0.981 as the mean of the two sets of measures. **Together with the z=0.995 quasar discussed at the end of the previous section,** *these two X-ray quasars form a pair aligned across the nucleus of NGC 3628* like so many other pairs which have now been reported across active galaxies (see Arp 1997; 1998).

Another striking aspect of this pair, however, is that they lie closely along the minor axis and very close to the nucleus of NGC 3628 (3.2 and 5.4 arc min). They have very similar redshifts, when transformed to the rest frame of NGC 3628, z=0.98 and 0.99. These redshifts are closely matched - a characteristic of many previous pairs of quasars across active galaxies - and demonstrate how unlikely it is that they are unassociated background objects. It is also noteworthy that these two redshifts are very close to the Karlsson value of quantized redshift of z=0.96. The remaining quasars in this field tend to have redshifts near the preferred peaks (for recent analyses of periodicities in z see Burbidge and Napier 2001).

In summary we see that in the case of the nearby galaxy NGC 3628, not only an HI plume but narrow PSPC X-ray filaments emerge along the minor axis connecting the z=2.15 and z=0.995 quasars back to the active nucleus. In addition the quasar in the filament has a counterpart, closely matched in redshift, on the other side of NGC 3628. (The recent Chandra map of the inner 2 x 2 arcmin (Strickland et al. 2001) shows X-ray material leading back to the NNE in the direction of the z=0.981 quasar. It would be of considerable interest to see what the rest of the Chandra field showed with regard to the narrow filament 4.1 arcmin to the SSE in which the two quasars are embedded.)

7. The Optical Objects Leading to the z=2.15 Quasar

It is particularly interesting that a chain of optical objects coincides with the narrow X-ray filament. It is conspicuous on both red and blue Poss II schmidt survey plates (Flesch and Arp 1999). This feature has been imaged with the ESO VLT at Paranal, Chile and is shown in color in the ESO Messenger (March 2002). Figure 4 here shows a FORS2 R band image of this optical filament. The pictures reveal that the object nearest the main galaxy is nebulous, shaped like a comet with a blue condensation at its head. Next along the filament to the SW are stellar-appearing objects, one quite red and one quite blue. The blue one turns out to be the z=0.995 X-ray quasar discussed previously (F2 in Fig. 4). Further along is a small, double, irregular galaxy or knot (F3) and then a larger, elongated and curved galaxy shape (F4). It has a narrow emission line spectrum of redshift z=0.153 (measured by

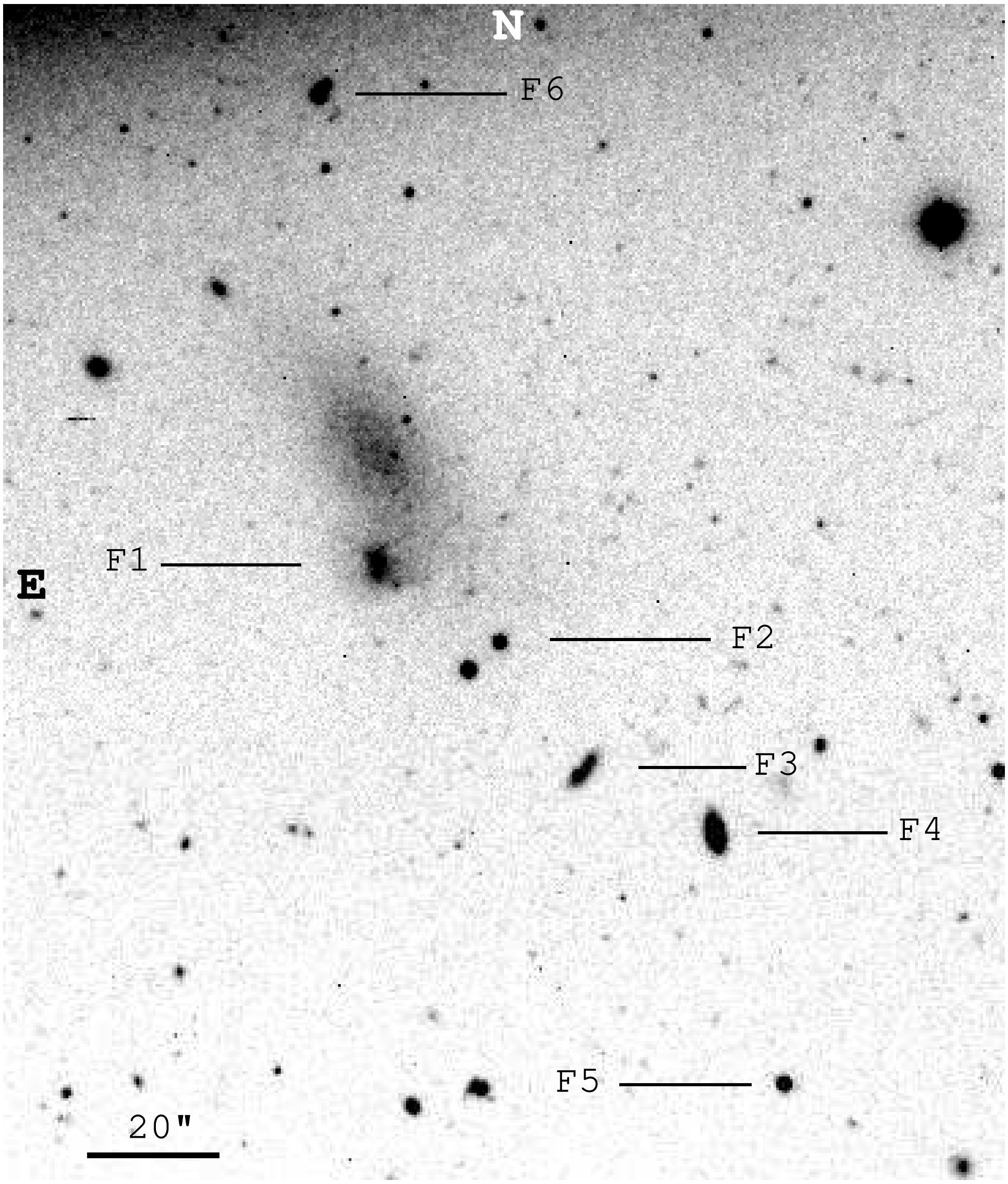

Fig. 4. *R* band exposure with VLT-FORS2 of the chain of objects coming SSW along the minor axis of NGC 3628. Quasars for Fig. 3 map and other optical objects in filament are identified as F1–F6. Available spectral data is summarized in Tab. 2. See ESO Messenger, March 2002 for a color picture of this SW region of NGC 3628.

Chu and Zhu in 1999 and Burbidge and Arp in 2000). Finally we encounter the z=2.15 quasar (F5) which is at the end of the X-ray filament. The data is summarized in Tab. 2.

There is perhaps a precedent for this in the optical filament in the giant radio galaxy CenA (NGC 5128). There the optical filament coincides with the direction of both the radio jet and the X-ray jet further in the interior. The optical filament consists of young stars and HII region-like emission lines, similar to a star forming arm in a spiral galaxy (Blanco et al. 1975; Arp 1986). We might then expect a low redshift emission line spectrum for the optical filament in NGC 3628. But in NGC 3628 there appear mostly discrete objects. The z=2.15 quasar is at the tip of the filament and there are two X-ray point sources in the filament as well as several blue and/or slightly extended optical objects.

In general, the narrowness of the filament requires that whatever is ejected in the X-ray jet (and in the case of Cen A the coincident radio jet) must be quite small. There would seem to be no candidates other than quasars, which are generally X-ray and radio sources and exhibit similar

Table 2. Objects in Fig. 4.

ID	B-V	z	R.A.(2000)	Dec.	Notes
F1	0.87	0.038	11 20 16.1	13 32 39	bright knot S
F2	0.51	0.995	11 20 14.7	13 32 27	X-ray, BSO
F3	0.66	-	11 20 13.9	13 32 05	double blue galaxy
F4	0.86	0.153	11 20 12.5	13 31 55	emission line, pec. galaxy
F5	0.20	2.15	11 20 11.9	13 31 23	obj. prism, Wee 51
F6	0.57	-	11 20 17.8	13 34 50	very blue, compact, double?

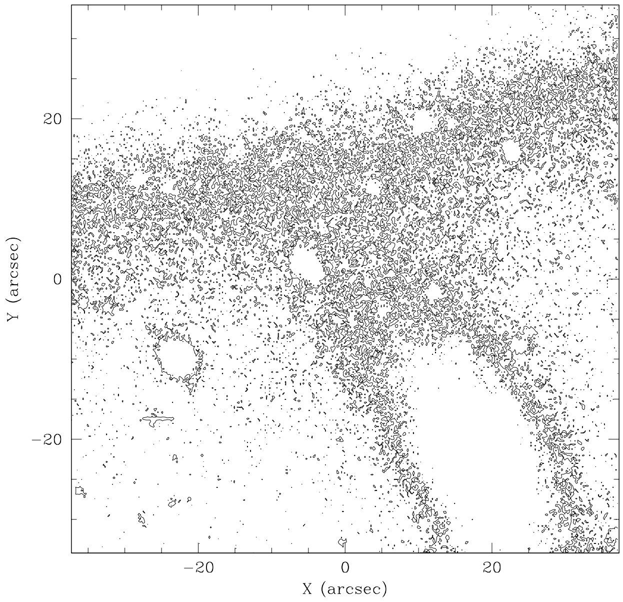

Fig. 5. Low surface brightness object in chain of objects along the SW minor axis of NGC 3628. From the R image of the VLT, the lowest contour here is 5 sigma above the sky background and suggests a connection with the main body of NGC 3628.

spectra to the active nuclei which are actually ejecting the material. Figures 3 and 4 could then represent a fortuitous moment when the quasar is just passing out beyond the filament. If this is the case we should be able to investigate the mechanics of the entrainment and excitation by obtaining further spectra.

Finally it should be remarked that with the obvious disruption of NGC 3628 it is expected that ejected material would be interacting with it as it emerged. One result would be to slow down the ejection speeds depending on the comparative densities of the matter involved and their particular route exiting the galaxy. This would result in ejecta being observed generally closer to their galaxy of origin and possibly disturbing the relation between redshift and distance from the galaxy (**i.e. the higher redshift objects being closer to the galaxy**) which is observed in ejections with less interaction (Arp 1999, Fig. 3).

8. The Low Surface Brightness Object

The most interesting spectrum to obtain, however is that of the comet shaped nebula at the beginning of the line of objects. To this end E. M. Burbidge, H. Arp and V. Junkkarinen placed a 3 arc sec wide slit of the 3 meter Lick telescope N-S across the nebula and its condensation. Night sky subtraction and processing revealed only one faint, narrow emission line but it was slightly extended and present on both 1800 sec red exposures. If the observed emission line in this nebulous object, F1, is Hα its redshift is z=0.038. This could represent entrained material in the ejection from the interior regions of NGC 3628 at about 11,000 km s^{-1} projected, or material of low intrinsic redshift or a mixture of both. The two quasars, F2 and F5, would have to be predominantly intrinsic in redshift. F3 is a double irregular object whose redshift is required. The spectrum of F4 looks like a narrow line galaxy at z=0.153 and may be non-associated although it is contorted. F6 is very blue and compact and requires a spectrum.

The comet shaped object, F1, is quite unusual and apparently not in a state of dynamical equilibrium. Since it is only about 25 arcsec from the quasar F2 it raises the possibility of interaction, either radiative or dynamical. It shows incipient resolution into compact objects in the R image. The bright condensation appears blue but there nevertheless may be considerable absorption which perhaps accounts for its very weak spectrum. Perhaps it resembles most a dwarf galaxy or a very large HII region. It is interesting to note that it has been suggested in the past that dwarf galaxies can be formed in disturbing events from larger galaxies (Arp 1996; Gallagher et al. 2001).

Fig. 5 is included here to show that the NE end of the low surface brightness object joins the main body of NGC 3628 in an apparently straight sided channel. The faint contour shown is 5 sigma above sky and suggests that the object is like a dwarf emerging from the central regions of NGC 3628. Perhaps the gas has been stripped out of a young, dwarf stellar assemblage. To explore this object further it would be important to get deeper, higher resolution spectra to ascertain the kind of stars which seem to be on the verge of resolution and the nature of the bright condensation at its S end.

9. Summary

In a completely searched area around NGC 3628 the known quasars are concentrated to the position of the starburst/AGN galaxy. At least four quasars are situated close to the edge of the galaxy disk. Further out the galaxy has prominent plumes of hydrogen gas and the quasars are well-aligned with key points on the plume contours. Along the minor axis of NGC 3628 there are a pair of quasars on opposite sides of the galaxy, a configuration of which there are now many known examples. The redshifts of these two X-ray quasars at z=0.977 and z=0.995 only differ by 0.018.

Perhaps most striking of all, a narrow X-ray and optical filament along the SSW minor axis connects the nucleus of NGC 3628 directly to a third quasar of z=2.15.

Preliminary spectroscopic investigation along the filament show a mixture of high and low redshift objects presumably reflecting a mixture of entrainment velocities of ejection and/or intrinsic redshifts.

We believe the improbability of finding quasars so close to NGC 3628, including two of them linked directly to the nucleus by an X-ray filament, combined with finding the galaxy to be so actively ejecting associated plumes of gas, optical and X-ray material in these directions is key confirmation of the previous evidence for ejection origin of quasars. A search for further quasars located within the solid angle of the bright disk of NGC 3628, spectroscopic identification of remaining quasar candidates in the field and further analysis of the optical filament should give insight into the physical mechanisms of their origin.

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