

Further Evidence that Some Quasars Originate in Nearby Galaxies: NGC3628

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Abstract. NGC3628 is a well-studied starburst/low level AGN galaxy in the Leo Triplet noted for its extensive out-gassed plumes of neutral hydrogen. Catalogued QSOs are shown to be concentrated around NGC3628 and aligned with HI plumes. The chance that the three nearest quasars would accidentally fall as close as they do is $\leq 10^{-2}$. The nearest quasar has a redshift of $z = 2.15$ and is at the tip of an X-ray filament emerging along the minor axis plume. Location at this point has an accidental probability of $\sim 2 \times 10^{-4}$. In addition an unusual optical filament also points directly at this quasar.

Key words: Galaxies: active - Galaxies:individual (NGC 3628) (*Galaxies:*) quasars: general - Radio sources: 21 cm radiation - Galaxies: X-rays

1. Introduction

NGC3628 is a nearby edge-on Sbc peculiar galaxy which is undergoing major internal dynamic activity which is, however, shrouded from our view by a prominent dust lane. 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 NGC3628, see Yaqoob et al (1995).

A prominent feature of NGC3628 is the long HI plumes being outgassed from the galaxy in two directions. The major plume to the ENE was first 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 out a weaker plume towards the south along the minor axis. The consensus explanation for the plume morphology is that it is consequential to a tidal encounter between NGC3628 and the nearby similar-sized spiral NGC3627, 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 NGC3628 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 contour about which Haynes et al. counseled caution. The velocity profile of the major plume is that of steady flow velocity away from the galaxy out to beyond the left edge of Fig1.

This excess hydrogen is originating from the central regions of NGC3628, 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. NGC3628 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 Arp (1997;1998) and others has shown a 7.5 sigma association of quasars with Seyfert galaxies, attributed to ejection from their active nuclei. As NGC3628 is a prominent nearby galaxy which is so clearly seen to be expelling material from an active nucleus, it is suggestive that we should look there for an observational test of the nearby-quasar model. And as seen in Fig. 1, there are indeed surveyed quasars in the near vicinity of NGC3628, even in near propinquity to its active disk. In this letter we will discuss evidence that these quasars are being vented out of NGC3628 along with the HI gas.

2. Quasars and candidates near NGC3628

Dahlem et al (1996) have enumerated a population of X-ray emitting sources in the ROSAT-detected hot gaseous halo of NGC3628. They found that this population density was over twice that of the wider background ($=1.5$ sigma deviation), but made no firm statistical statement due to the small numbers involved. Dahlem et al. note that the emission properties of these sources point to their identification as either AGN (QSOs) or X-ray binaries, and as there is no physical model for X-ray binaries to be prevalent in the galaxy's halo, their identification as AGN

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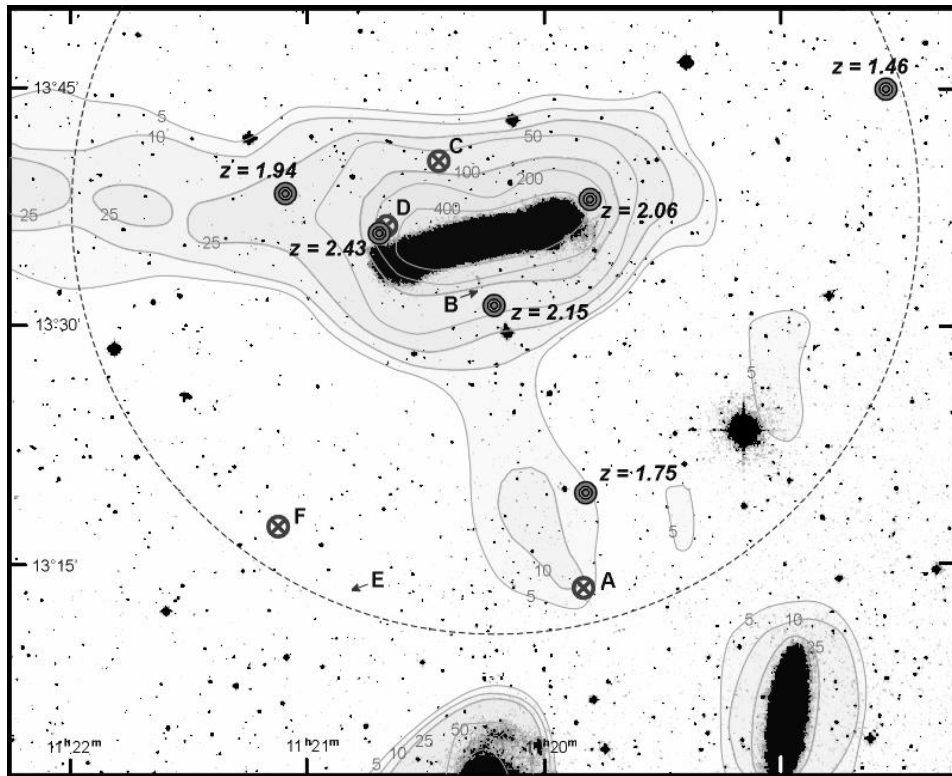


Fig. 1. Isophotal contours of neutral hydrogen (HI) coming from the starburst/AGN galaxy NGC3628 (from Haynes, Giovanelli and Roberts (1979)). Catalogued quasars are annotated with their redshift values, objects marked with a circled X are probable quasars (see table 1), and small arrows mark possible quasars. The search field of Weedman (1985) is bounded by the dashed line. Objects surveyed by Weedman (1985) and by Dahlem et al (1996) are included in Fig 1. Six catalogued QSOs are displayed, and six QSO candidates, the details of which are presented in table 1.

(QSO) is indicated. In the standard model all these QSOs are placed into the background, their greater density near NGC3628 notwithstanding. In the alternative model advanced by Arp (1987), G.R. Burbidge and others, most of these QSOs are local to the NGC3628 environment, which accounts simply for their observed overdensity near many such galaxies, see e.g., E.M. Burbidge (1999).

TABLE 1 Objects in Fig 1.

ID	Survey#	QSO	R.A.(2000)	Dec.	Notes
A	Wee 49	prob	11 19 49	13 13 24	two em lines
B	Dahl 8	poss	11 20 15	13 32 30	X-ray, ext. red
C	Dahl 13	prob	11 20 26	13 40 25	X-ray,BSO
D	Dahl 15	prob	11 20 40	13 36 20	X-ray,BSO,dbl
E	Wee 53	poss	11 20 51	13 13 36	one em line,brd
F	Wee 56	prob	11 21 10	13 17 54	one em line

Thus we have 10 confirmed or probable QSOs in the surveyed area of figure 1, of which 8 are within the galaxy's plume contours. The average background density which Weedman found for his 20 CFHT 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 $+8/-6$ which background density is plotted in Fig. 2. It is seen that the closest quasars to NGC3628 reach a density of about 100/sq. deg. The chance of finding the the two closest quasars at 19.7 and 19.9 mag. is only .002 (using Poisson statistics). Of the three closest, the $z = 2.43$ is at 21.2 mag. and probably absorbed by the galaxy, but still makes the probability of chance concentration even smaller. Also, this is based on an over-prediction of background numbers because, as we have seen the Weedman survey set on some very active

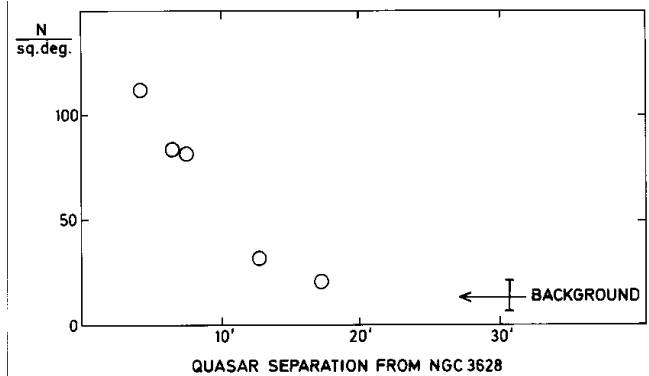


Fig. 2. The density of catalogued quasars at each distance from NGC3628. is plotted. The arrow marks the upper limit to average background density of $1.75 \leq z \leq 2.5$ quasars. The area blocked by NGC3628 has been excluded.

galaxies and then only used plates with the most quasars below $m_{4500} = 20$ mag.

3. Quasars in the galactic disk of NGC3628

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. Apparently this is a double quasar of which the second component remains to be observed spectroscopically. 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 NGC3628 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 NGC3628 and nearby quasars. One quasar ($z=1.94$) lies at the base of the main ENE plume, coincident onto the optical jet imaged by Kormendy and Bahcall (1974). Another quasar ($z=1.75$) lies in the southern plume coincident with a thickening of the plume, and the probable quasar Wee49 (Weedman 1985) lies, very interestingly, right at the tip of the southern plume. Thus these quasars are not only aligned with the southern plume, but positioned at contour nodes. This is strongly indicative of physical association, and implies that these quasars and HI plumes have come out of NGC3628 in the same physical process.

5. X-ray Ejection from the Nucleus of NGC3628

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 filament coming from the bright X-ray nucleus continuously out to end on the $z=2.15$ quasar.

If we adopt the last X-ray source as the end of the filament, then the quasar falls essentially on 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} .

The 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 should be investigated spectroscopically. Optically this latter source appears slightly extended so it should be particularly interesting. At about an equal distance on the other side of the NGC3628 nucleus, along the N minor axis, is a brighter X-ray source which is identified

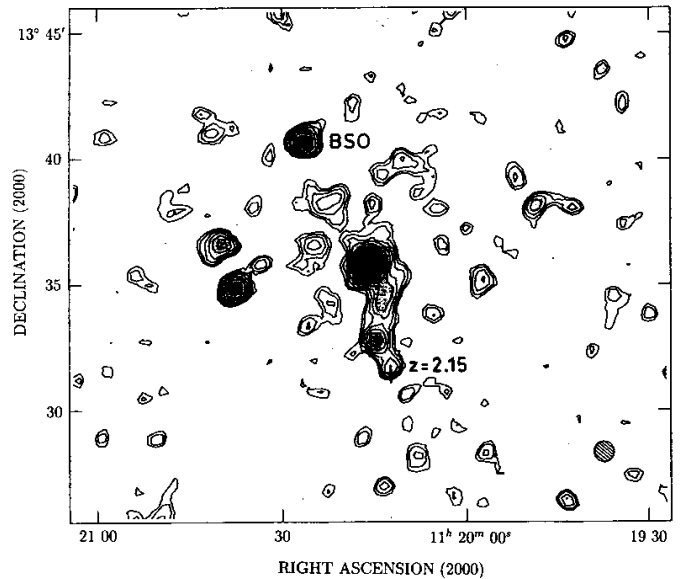


Fig. 3. The 0.75 keV band map of NGC3628 from Dahlem et al. (1996). The optical position of the $z = 2.15$ quasar is marked by a plus at the tip of the filament coming out along the minor axis to the SSW. BSO marks a blue stellar object identified with the X-ray source Dahlem #13.

with an $E = 18.6$ mag., blue stellar object (BSO), shown as object C on Fig. 1. This is almost certainly a quasar and when confirmed will form a pair across NGC3628 like so many other pairs which have now been found across active galaxies (see Arp 1997; 1998).

6. The Optical Filament Leading to the $z = 2.15$ Quasar

Fig. 4 shows a processed portion of the Palomar Schmidt E plate (POSSII). A short, narrow optical filament emerges along the minor axis nearly coincident with the X-ray filament pictured in Fig. 3. The simplest model would be that this is gas from the interior regions of NGC3628 which has been entrained in the ejection of whatever is coming, or has come out, along the line of the X-ray ejection. The $z = 2.15$ QSO (Wee 51) is identified with Dahlem et al. (1996) object #7, also identified by Read, Ponman and Strickland (1997) as their object #2. Optical identification in Fig.1 of the optically-extended, point X-ray object Dahlem et al. (1996) #8, is enabled by positional projection from the QSO using both papers' co-ordinates.

There is an excellent precedent for this kind of an optical filament in the giant radio galaxy CenA (NGC5128). 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). Hence we would expect a low redshift emission line spectrum for

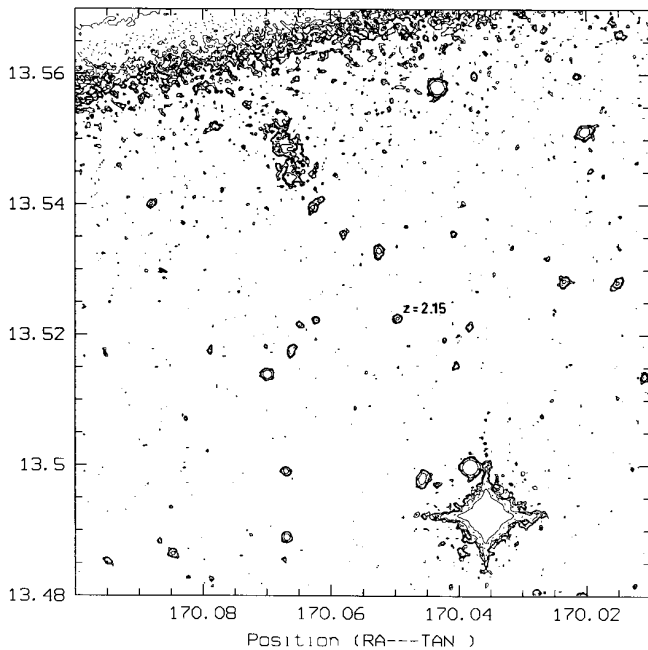


Fig. 4. An optical filament coming out along the minor axis of NGC3628 (edge of galaxy at upper left). The knots leading to the $z = 2.15$ quasar are blue and slightly extended and lie in the X-ray filament pictured in Fig. 3. Image from processed, POSSII Schmidt plate.

the optical filament in NGC3628. But in NGC3628 the $z = 2.15$ quasar is at the tip of the filament and there is an X-ray point source in the filament as well as several blue and/or slightly extended optical objects. We should be able in this case to investigate the mechanics of the entrainment and excitation if better resolution plates and spectra are obtained.

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 spectra to the active nuclei which are actually ejecting the material. Figures 3 and 4 would then represent a fortuitous moment when the quasar is just passing out beyond the filament.

7. Redshift vs separation from galaxy

The redshifts of the quasars in Fig. 1 decrease as their projected angular distances from NGC3628 increase. This has been found previously for galaxy-quasar associations but in the NGC3628 case the z vs $\ln r$ plot decreases less steeply than for quasars coming out only along galaxy minor axes (Arp 1999, Fig. 3). This may be because we are dealing with quasars mostly around $z = 2$ here, or it may mean that the quasars here are interacting with the

material of the galaxy and being slowed or captured from their less inhibited escape along minor axes.

8. Summary

In a completely searched area around NGC3628 the known quasars are concentrated to the position of the starburst/AGN galaxy. Two quasars and a probable quasar are situated on the rim of the galaxy disk. The galaxy has two prominent plumes of hydrogen gas and quasars are well-aligned with key points on the plume contours. On the minor axis of NGC3628 there are a quasar and a probable quasar on opposite sides of the galaxy, which is a prototypical configuration. *Perhaps most striking of all, a narrow X-ray and optical filament points along the minor axis of NGC3628, directly to the closest quasar.*

We believe the improbability of finding quasars so close to NGC3628, including one of them linked directly to the nucleus, combined with the improbability of finding the galaxy to be so actively ejecting associated plumes of gas, optical and X-ray material presents a key confirmation of the origin of quasars. A search for further quasars located within the solid angle of the bright disk of NGC3628, spectroscopic identification of the surrounding X-ray BSO's and analysis of the optical filament would give further insight into the physical mechanisms of their origin.

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