

DIRECT IMAGING OF THE EXTREMELY LARGE HOST GALAXY AND GAS CLOUD SURROUNDING THE QUASAR 3C 275.1

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ABSTRACT

The quasar 3C 275.1 ($z = 0.55$) was previously shown to lie in a large “rotating” gas cloud (major axis ≈ 100 kpc) at the center of a rich cluster of galaxies. We present CCD imaging observations of the 3C 275.1 field using r , v , and redshifted [O II] $\lambda 3727$ filters. Our image of the nebulosity in redshifted [O II] shows an elliptical substrate containing several bright knots. The luminosity of the gas cloud in [O II] $\lambda 3727$ is 1.4×10^{43} ergs s^{-1} . Both the emission line-free r image and the v image after [O II] subtraction indicate that the quasar host galaxy is extremely large and luminous ($M_B \approx -24.3$). The host galaxy’s luminosity, dimensions, and position at the cluster center suggest that it may be a cD or a “proto-cD”. Since the cluster (or quasar) is a strong X-ray source ($L_x = 3.6 \times 10^{44}$ ergs s^{-1}), we suggest that the nebulosity observed may be accreted matter from a “cooling flow” of the intracluster medium, and that this flow both powers the quasar nucleus and has induced extensive star formation, thereby accounting for the host galaxy’s extreme luminosity and blue color. Alternatively, the quasar and the surrounding “proto-cD” and gas cloud may be the result of repeated galaxy collisions. These observations suggest that quasars lying near the centers of clusters of galaxies may be fed by cooling flows or by multiple interactions, and that quasar host galaxies at $z \geq 0.6$ might evolve into present-epoch cD galaxies as a result of star formation in the accreting material.

Subject headings: galaxies: clustering — galaxies: nuclei — galaxies: X-rays — quasars

I. INTRODUCTION

Direct optical imaging of the quasar 3C 275.1 ($z = 0.55$) provided evidence that this object lies at the center of a rich cluster of galaxies, and subsequent spectroscopy of the surrounding galaxies confirmed the association (Hintzen, Boeshaar, and Scott 1981; Hintzen 1984). Recent long-slit spectroscopy has shown that the quasar nucleus is surrounded by an extremely large elliptical cloud of ionized gas whose velocity curve resembles solid-body rotation (Hintzen and Stocke 1986, hereafter HS). The nebulosity’s large size (major axis ≈ 100 kpc), comparative spatial uniformity, and peculiar velocity curve are unique among quasar nebulosities studied to date. Also, either the quasar, the cluster, or both are X-ray sources, with a total X-ray luminosity of $3.6 (\pm 1.5) \times 10^{44}$ ergs s^{-1} in the 0.5–4.5 keV band (HS).

Smaller gas clouds of less regular form have been found surrounding low-redshift quasars and have been interpreted as debris from interactions between the quasar host object and neighboring galaxies (Stockton 1976; Stockton and MacKenty 1983; Hutchings and Campbell 1983). HS similarly suggested that the larger, more uniform 3C 275.1 nebulosity may have arisen from numerous high-speed and there-

fore less disruptive interactions with other galaxies in the dense cluster. HS also suggest two further possibilities: The nebulosity could be accreting material from a cluster “cooling flow” of the type seen in low-redshift clusters which are X-ray sources, or, if the quasar nucleus is the X-ray source, the nebulosity could result from a wind emanating from the host galaxy.

We have obtained direct CCD images of the 3C 275.1 field using v , r , and redshifted [O II] filters to study the ionized gas cloud and to determine the gross characteristics of the quasar host galaxy.

II. OBSERVATIONS

On 1985 June 21 UT direct imaging data for the 3C 275.1 field were obtained using a Texas Instruments 800×800 CCD at the prime focus of the KPNO 4 m telescope. The resulting CCD frames cover a field approximately $2'7 \times 2'7$ with a scale of $0'29$ per pixel. Three 300 s integrations were taken using a v filter (central wavelength [CW] = 5460 \AA ; full width at half-maximum [FWHM] = 873 \AA). Four 300 s integrations were obtained in an r filter chosen to largely exclude [O II], [O III], and $H\beta$ at the quasar’s redshift (CW = 6470 \AA , FWHM = 1208 \AA). Finally, two 900 s integrations were taken using an interference filter centered on the redshifted [O II] $\lambda 3727$ line (CW = 5809 \AA , FWHM = 104 \AA , hereafter “the [O II] filter”).

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Variations in seeing and focus produced differences in image sharpness: For stellar images the measured FWHMs were 1".2 in r , 1".4 in v , and 1".8 in the [O II] filter. Instrumental magnitudes were measured for several stars in each frame. For each filter these stellar magnitudes vary by only 0.5%–0.7% between frames, indicating photometric conditions.

A photometric calibration field in NGC 7790 was observed in both v and r in 1985 June 20 and on 1985 June 21, but since thin clouds were present these data have been used only to determine the slope of the $v - r$ (instrumental) versus $V - R$ (standard) relation. Subsequent v and r frames of the 3C 275.1 field and photometric standard fields in NGC 4147 and NGC 2419 were obtained with the KPNO cryogenic camera in direct mode on 1986 March 15. These latter observations, taken under photometric conditions, were used to determine calibrated V and $(V - R)$ magnitudes for five bright stars and galaxies in the cryocam direct frames of 3C 275.1. These secondary standards were then used to determine photometric zero points for the v and r data from our earlier prime focus CCD observations of the 3C 275.1 field. Comparison of the various data frames and intercomparison of the NGC 4147 and NGC 2419 calibration fields indicates that the derived photometric zero points are accurate to better than 0.1 mag. The magnitudes adopted for the NGC 7790, NGC 4147, and NGC 2419 photometric standard fields were taken from Christian *et al.* (1985).

In order to calibrate the [O II] frames, the 3C 275.1 field and Feige 34 were observed on 1986 May 6 using the [O II] filter with an RCA CCD camera on the Steward Observatory 2.2 m telescope. Two 300 s frames were obtained for the 3C 275.1 field. Two frames of Feige 34 were also obtained, one a 5 s integration and the other, 10 s. Using the fluxes for Feige 34 provided by Barnes and Hayes (1984), the flux of a bright star in the 3C 275.1 field was determined. The two flux measurements for the 3C 275.1 field star agree to better than 0.5%, as do the two measurements for Feige 34.

III. ANALYSIS

The position of the quasar in each frame was determined using a Gaussian fit and each frame was shifted using bicubic splines so that the quasar's position was the same for all frames and all filters. Then, for each filter, the various frames were summed, the sky background was subtracted, and the summed frames in each filter were scaled to 900 s exposures at the zenith.

The v image, which includes [O II] $\lambda 3727$ at the quasar's redshift, was then used to subtract continuum contributions to the [O II] image. First, the v image was convolved with the sum of two Gaussians chosen so that the convolved stellar image profiles in v matched the stellar profiles in the [O II] image. The proper combination of Gaussians, one to correct the image core and one for the image wings, was determined by trial and error. It was then necessary to determine the relative flux of continuum emission in the v and [O II] filters. This intensity ratio, $O II/v$, is roughly 0.12, the ratio of the widths of the filters. However, $O II/v$ also depends on object color. To determine this dependence, the $O II/v$ ratio was

plotted as a function of color for four stars and one bright galaxy in the 3C 275.1 field. A least-squares fit to these data, which range from $(V - R) = 0.45$ –1.15, yields

$$O II/v = 0.047 (V - R) + 0.081,$$

implying a very modest dependence on color.

To produce an [O II] image with continuum flux removed, the "seeing convolved" v image, multiplied by an appropriate $O II/v$ value, was subtracted from the original [O II] image. Over most of the frame $O II/v$ was set to a constant value, 0.15, appropriate for a "typical" galaxy with $(V - R) = 1.5$. Since the quasar has a blue nucleus and shows a color gradient, $O II/v$ was allowed to vary with radius in the quasar's immediate vicinity, in accordance with the measured $(V - R)$ color. Trial runs with a range of $O II/v$ ratios demonstrate that the resulting images are quite insensitive to the ratio used. In fact, for any plausible range of $O II/v$ ratios the only significant change in the continuum-subtracted [O II] image is at the inner core of the image (2".5 radius) where the flux is dominated by the continuum light of the quasar. Outside the stellar core of the quasar [O II] $\lambda 3727$ contributes at least 50% of the light in the narrow-band filter, so changing the $O II/v$ ratio has little effect. The final continuum-subtracted [O II] image is presented in Figure 1 (Plate L1), with the original [O II] image and a deep R frame for comparison.

In the continuum-subtracted [O II] image the nebulosity "major axis" extends 12" (40 pixels). The quasar nucleus lies on a ridge of emission coincident with the major axis (Fig. 1*d*). The integrated [O II] $\lambda 3727$ flux within a 6".5 radius of the quasar nucleus is 6.5×10^{-15} ergs cm^{-2} s^{-1} , implying an [O II] $\lambda 3727$ luminosity of 1.4×10^{43} ergs s^{-1} , where we estimate the uncertainty to be about 20% (in the present paper we assume $H_0 = 50$ km s^{-1} Mpc $^{-1}$, $q_0 = 0$). The derived [O II] $\lambda 3727$ luminosity agrees fairly well with the less accurate value derived by HS (9×10^{42} ergs s^{-1}) from spectroscopic observations at three position angles.

An image modeling program (W. Romanishin and P. Hintzen, in preparation) was then used to fit galaxy models to the continuum nebulosity underlying the quasar. The r image was used, since the r passband largely excludes oxygen and hydrogen emission: the r filter transmission at 5800 Å (redshifted [O II] $\lambda 3727$) is only 20%, compared with 80% at 6500 Å. Assuming an elliptical galaxy model and correcting for the residual [O II] $\lambda 3727$ contribution, the best fit yields a point source-to-galaxy flux ratio of 1.4 and a galaxy effective radius (the radius containing half of the galaxy's light) of $r_e = 6''$ ($-3'' + 9''$) or $\log r_e$ (kpc) = 1.71 ± 0.4 (90% confidence). Assuming $H_0 = 50$, $q_0 = 0$, and a K -correction in R of 0.86 mag (Coleman, Wu, and Weedman 1980), the elliptical galaxy fit implies a total absolute magnitude for the galaxy of $M_R = -26.0 \pm 0.4$. For a normal elliptical $(B - R) = 1.8$, implying $M_B = -24.2$ in the present case. Both the effective radius and the absolute magnitude derived indicate that the 3C 275.1 "host" is an extremely luminous galaxy (Fig. 2), comparable to the brightest cD's (e.g., Oemler 1976). An acceptable fit to the image profile can also be obtained using a

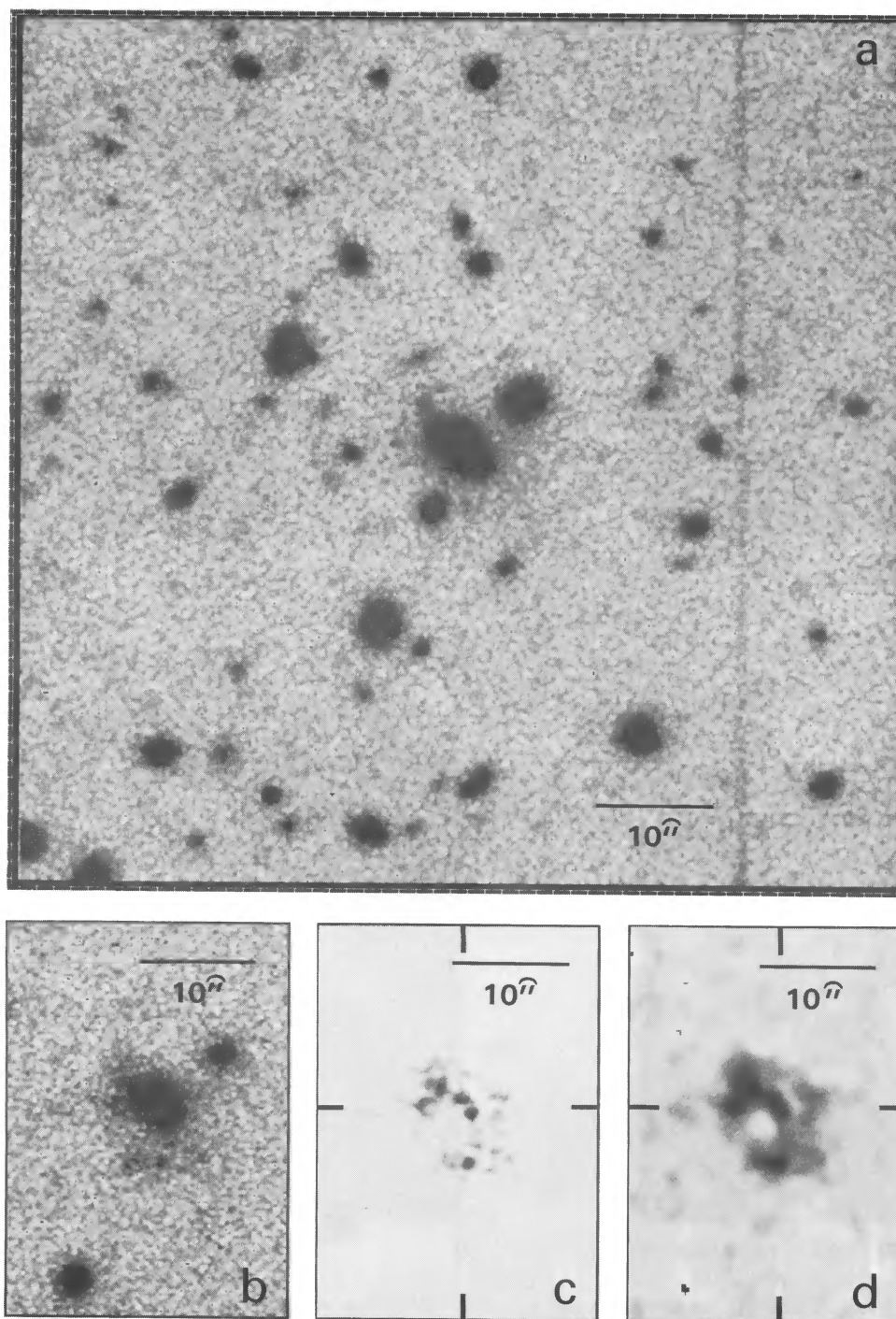


FIG. 1.—High-contrast prints of deep direct CCD images of the 3C 275.1 field and of the nebulosity surrounding the quasar. In each case, north is at the top, east is to the left, and the image scales are identical ($10''$ bars are shown). (a) The large print is a reproduction of the central $1'.24 \times 1'.24$ portion of a 1200 s integration in the r filter. The quasar nucleus ($z = 0.55$) at the field center is the brightest object in the field ($R = 18$ within a $2''$ radius aperture), although image saturation reduces the apparent contrast between the quasar and the other galaxies in the field ($R = 19.8\text{--}24$). The large elliptical nebulosity surrounding the quasar nucleus in r must represent continuum emission from the quasar host galaxy, since the R passband used effectively excludes [O II], [O III], and $H\beta$. The high density of cluster galaxies surrounding the quasar is evident. The three smaller pictures below are [O II] $\lambda 3727$ images of the region immediately surrounding the quasar. (b) The left print, taken from the original redshifted [O II] image, shows the quasar and two nearby galaxies. (c) and (d) The central and right prints, which are identical except for the printing transfer function, show the same data after continuum contributions have been subtracted from the [O II] data. Tick marks indicate the position of the quasar nucleus. Both the elliptical [O II] substrate and the bright knots discussed in the text are evident. The central ridge of emission seen in (d) coincides with the quasar nucleus, while a large “hole” in the [O II] emission is evident southeast of the nucleus. The disappearance of the adjacent galaxies demonstrates the accuracy of the continuum subtraction technique.

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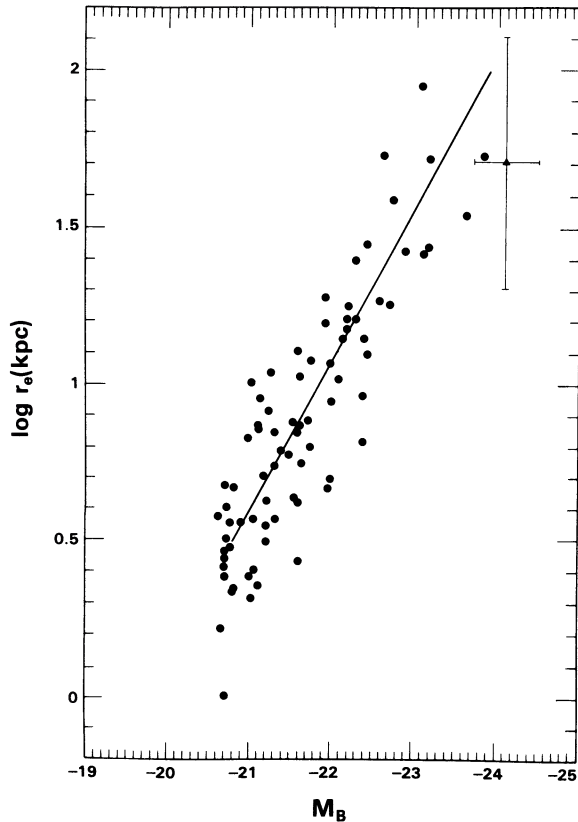


FIG. 2.—Blue absolute magnitude is plotted as a function of the logarithm effective radius for the 3C 275.1 “host galaxy” (triangle) and for the normal elliptical galaxies (filled circles) discussed by Romanishin (1986*a*). The cross representing the 3C 275.1 data subtends the 90% confidence interval. The 3C 275.1 parameters represent continuum data only, since the r image, corrected for minimal contamination by [O II] emission, was used in the analysis.

spiral galaxy model, although a spiral model yields an even higher luminosity.

Attempts to fit underlying galaxy models to the v image of 3C 275.1 are complicated by the presence of the nebosity responsible for the [O II] emission, since that nebosity may have developed independently of the original “host” galaxy. As a first approximation to a v image containing only starlight, the narrow-band [O II] image was subtracted from the seeing-convolved v image. Assuming a K -correction appropriate for an E galaxy, we derive $M_V = -25.8 \pm 0.3$ for an E galaxy model profile (the 90% confidence interval quoted includes only the uncertainty in the fit parameters). Assuming an intrinsic $(B - V)$ appropriate for an E galaxy then implies $M_B = -24.9$. This derived M_B is inconsistent with that derived from the r image with E galaxy parameters, implying that the starlight is bluer than an E galaxy. If we assume colors and a K -correction appropriate for an Sbc galaxy, we derive $M_B = -24.2$ from the r image and $M_B = -24.4$ from the v image, again using an E galaxy profile. (Note that M_B derived from the r image for the E and Sbc colors is identical, as the r filter really measures the B passband light in the rest

frame of 3C 275.1.) Thus, the continuum light of the host galaxy plus nebosity is bluer than an E galaxy of intrinsic $(B - R) = 1.8$ and has colors more like an Sbc galaxy, which has intrinsic $(B - R) = 1.3$. Of course, we cannot tell at this point whether the blue component is starlight associated with current star formation in the nebosity, in which case the underlying galaxy might be a “normal” red elliptical, or whether it is part of the host galaxy, in which case the galaxy is intrinsically blue.

Evidence for enhanced luminosity in the host galaxy is apparent in Figure 2. The model fit to the R image of the host galaxy lies about 0.8 mag too bright for its effective radius compared to normal giant ellipticals (Romanishin 1986*a*). Because any continuum contribution from the diffuse nebosity would tend to cause an overestimate of r_e , the excess luminosity in B compared with the standard relation may be even larger than 0.8 mag. The data therefore suggest significant recent star formation in the quasar host galaxy.

IV. DISCUSSION

The data presented above indicate that 3C 275.1 lies in a parent galaxy of cD-like dimensions and luminosity ($M_R = -26$ and $r_e = 55$ kpc for an elliptical model). The elliptical gas cloud which is approximately centered on the quasar has a semimajor axis of about 50 kpc and an [O II] $\lambda 3727$ luminosity of 1.4×10^{43} ergs s^{-1} ($3.7 \times 10^9 L_\odot$). While the nebosity as imaged in [O II] is more uniform than the quasar-associated gas clouds discussed by Stockton and MacKenty (1983), it is evident from Figure 1 that the nebula displays considerable structure, including several bright knots with [O II] $\lambda 3727$ luminosities of about 7×10^{41} ergs s^{-1} each. The quasar nucleus lies on the ridge of [O II] emission which runs along the nebosity’s major axis (Fig. 1*d*). A large “hole” in the [O II] emission is evident southeast of the nucleus.

As discussed by HS, the large [O II] luminosity and apparent rotation of the 3C 275.1 nebosity are reminiscent of Spinrad and Djorgovski’s (1984*a, b*) results for distant 3C radio galaxies, in which those authors note that “The strong [O II] emission is often much extended and inclined, showing a considerable velocity amplitude.” On the other hand, the [Ne v] $\lambda 3426$ /[O II] $\lambda 3727$ ratio for 3C 275.1, derived from the HS spectra, is 0.23. This value is much larger than typical values for Spinrad’s (1982) high-redshift 3C radio galaxies, but it is identical to Cohen and Osterbrock’s (1981) average for narrow-lined radio galaxies.

These new data may shed light on the three mechanisms suggested by HS to explain the 3C 275.1 gas cloud.

The hypothesis that the gas cloud results from a wind flowing from the host galaxy suffers from at least two apparent problems, as noted by HS. First, wind velocities due to X-ray heating from the quasar nucleus should decrease at large distances, just the opposite of what is observed in the [O II] “rotation curve” (HS). Second, the observed [O III]/[O II] flux ratio suggests a low-ionization heating mechanism. We therefore tentatively dismiss the “galactic wind” hypothesis.

HS also suggest that “the observed comparatively uniform nebosity may be the result of the combined debris of

numerous high-speed, low-efficiency interactions with other cluster members." Star formation from such debris might reasonably be expected to account for the quasar host galaxy's extraordinary luminosity in the continuum. On the other hand, multiple random galaxy collisions should not result in the orderly "rotation curve" observed in the nebulosity.

Finally, since the cluster and/or the quasar is a strong X-ray source, we consider the possibility that both the enormous gas cloud and the host galaxy's great luminosity are the result of a "cooling flow" associated with the cluster X-ray source (HS). Fabian *et al.* (1986, hereafter FANM) have described the expected results of the cooling flow model. The known attributes of the 3C 275.1 system are in accord with the FANM predictions:

1. The quasar lies at the center of a rich cluster of galaxies, where a cooling flow would be expected.
2. FANM predict that the narrow-line emission regions of some quasars will be extended over a scale of about 10 kpc. The 3C 275.1 gas cloud is an order of magnitude larger than this.
3. According to FANM, cooling flow line emission regions generally show an [O II]/[O III] ratio exceeding 1, indicating low ionization. This is also the case in the 3C 275.1 nebulosity, which has an [O II] λ 3727/[O III] λ 5007 flux ratio of about 1.9, compared with a value of 1.1 for the quasar nucleus (HS).
4. The 3C 275.1 long-slit spectra show that regions near the QSO nucleus are more highly ionized than the outer regions of the nebula (HS, Fig. 2), as FANM predict for cooling flows around active nuclei.
5. Finally, the cooling flow would be expected to result in extensive star formation, which would explain the 3C 275.1 host galaxy's great luminosity and blue color.

Calculation of cooling flow-induced star formation rates based on X-ray data is currently subject to uncertainties of at least an order of magnitude. Until recently it was assumed, in view of the large mass flows inferred from X-ray observations of low-redshift clusters, that cooling flows must be biased toward low-mass stars (Fabian, Nulsen, and Canizares 1982; Sarazin and O'Connell 1983). However, recent studies suggest that both heat conduction and heating due to galaxy motions will significantly reduce gas cooling rates, in which case abnormal initial mass functions need not be postulated (Bertschinger and Meiksin 1986; Miller 1986).

Optical evidence of apparent cooling flow-induced star formation has been found in the giant elliptical galaxy PKS 0745–191, in NGC 1275, and in a sample of central galaxies in southern clusters (Fabian *et al.* 1985; Romanishin 1986*b*; Johnstone, Fabian, and Nulsen 1986). In the case of PKS

0745–191, which generally resembles the 3C 275.1 host galaxy in absolute magnitude, blue color, and the presence of extended [O II] emission, Johnstone *et al.* find that a star formation rate of $100 M_{\odot} \text{ yr}^{-1}$ is necessary to explain the observed strength of the optical emission lines and the 400 Å break (assuming a normal initial mass function and ignoring "dark matter"). Such star formation rates could, over the lifetime of the cooling flow, create a giant elliptical galaxy or a cD galaxy, or completely change the character of a previous central galaxy in the cluster (e.g., Friaca 1986). In view of the great extent of optical emission line regions apparently associated with cooling flows (e.g., 20–100 kpc: Cowie *et al.* 1983), star formation in cooling flows would seem particularly suited to producing the stellar components of large scale height and the stellar halos seen in cD galaxies.

Since 3C 275.1 is the first quasar at the center of a rich cluster to be identified and studied in detail, we do not know whether this object is typical of quasars in rich clusters. Few, if any, low-redshift QSOs are in cD galaxies, but this is not surprising, since very few, if any, low-redshift QSOs lie at the centers of rich clusters, where cooling flows are apparently strongest. On the other hand, Yee and Green (1986) report evidence that quasars at moderate redshifts ($z \approx 0.6$) are much more likely to be members of rich clusters, a circumstance that may be related to evolution of the cluster and the intracluster gas (e.g., Friaca 1986; De Robertis 1985; Stocke and Perrenod 1981). Quasar activity associated with the production of giant galaxies or cD's at $z \approx 0.6$ (e.g., 3C 275.1) would have died out by the present epoch, leaving, we presume, a normal cD at the cluster center.

In summary, the 3C 275.1 results suggest that quasars lying near the centers of clusters or groups of galaxies may be fed by cooling flows or multiple interactions, and that quasar host galaxies at large redshifts may have evolved into present-day cD galaxies as a result of cooling flow-driven or interaction-driven star formation. X-ray studies have demonstrated that while the largest cooling flows generally occur in rich clusters, weaker flows are also found in some poor clusters (e.g., FANM and references therein). Cooling flow-induced quasar formation might therefore also help explain the presence of quasars in poor clusters.

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