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THE APPARENTLY NORMAL GALAXY HOSTS FOR TWO LUMINOUS QUASARS[1]

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ABSTRACT

HST images (with WFPC2) of PHL 909 ($z = 0.171$) and PG 0052+251 ($z = 0.155$) show that these luminous radio-quiet quasars each occur in an apparently normal host galaxy. The host galaxy of PHL 909 is an elliptical galaxy ($\sim$E4), and the host of PG 0052+251 is a spiral ($\sim$Sb). Both host galaxies are several tenths of a magnitude brighter than L^*, the characteristic Schechter luminosity of field galaxies.

The images of PHL 909 and PG 0052+251, when compared with *HST* images of other objects in our sample of 20 luminous, small-redshift ($z \leq 0.30$) quasars, show that luminous quasars occur in a variety of environments. The local environments of the luminous quasars range from luminous ellipticals, to apparently normal host galaxies, to complex systems of interacting components, to faint (and as yet undetected) hosts.

The bright H II regions of the host galaxy of PG 0052+251 provide an opportunity to measure directly the metallicity of the host of a luminous quasar, to establish an upper limit to the mass of the nuclear AGN (i.e., the putative black hole source), and to test stringently the cosmological hypothesis that the galaxy and the quasar are both at the distance indicated by the quasar redshift.

The moderately luminous host galaxies of PHL 909 and PG 0052+251 are obvious on the *HST* images. Normalizing the limits of detectability using short exposures in which the host galaxies of PHL 909 and PG 0052+251 are easily observed, we estimate that we could have detected similar host galaxies as faint as 0.5 magnitudes less than L^* in the longer exposure *HST* images that have not yet shown host galaxies. The details of the PSF subtraction are unimportant for the determination of the host galaxy morphologies and luminosities; the major and minor axes measured by subtracting very different stellar PSFs are the same to $\pm 5\%$ and the host galaxy magnitudes are the same to ± 0.1 mag.

Subject headings: galaxies: structure — quasars: individual (PHL 909, PG 0052+251)

1. INTRODUCTION

We present *Hubble Space Telescope* (*HST*) images of PHL 909 and PG 0052+251 that show that these two quasars reside in apparently normal galaxies; these images provide unambiguous evidence that luminous radio-quiet quasars can be found in prosaic environments. The evidence is displayed in the accompanying seven figures and the results are summarized in Table 1. The reader is urged to at least glance at the figures before proceeding.

PHL 909 and PG 0052+251 are two of the 20 luminous, nearby quasars whose galactic hosts and local environments are being studied in our *HST* imaging program. The images of the first eight quasars in this sample have been presented previously, along with a detailed discussion of the analysis procedures (see Bahcall, Kirhakos, & Schneider 1994, 1995a; hereafter Paper I and Paper II). In addition, the quasar PKS 2349−014 has been caught in the act of what appears to be a collision with diffuse galactic material (Bahcall, Kirhakos, & Schneider 1995b, hereafter Paper III). The *HST* images of 3C 273 provide remarkably detailed information on the optical counterpart of the radio jet (Bahcall et al. 1995c, hereafter Paper IV).

All of the quasars in the sample have high luminosities and low redshifts; they were chosen from the Véron-Cetty & Véron (1993) catalog and have $z \leq 0.30$ and $M_V \leq -22.9$ for $H_0 = 100$ km s^{-1} Mpc^{-1} and $\Omega_0 = 1.0$. These cosmological parameters are used throughout the present paper. The redshift of PHL 909 is $z = 0.171$ and the apparent visual magnitude is $V = 15.7$ ($M_V = -22.9$). The redshift of PG 0052+251 is $z = 0.155$ and the apparent visual magnitude is $V = 15.4$ ($M_V = -23.0$). Both PHL 909 and PG 0052+251 are radio-quiet (Véron-Cetty & Véron 1993; Kellerman et al. 1989; Condon et al. 1981).

This paper is organized as follows. The observations are described in § 2. The images and the measurements are presented in § 3. The principal results and conclusions of this paper are summarized and discussed in § 4.

There have been a number of previous investigations of the nebulosity around PG 0052+251 using ground-based observations (see, e.g., Boroson, Oke, & Green 1982; Boroson, Person, & Oke 1985; Stockton & MacKenty 1987; Hutchings, Janson, & Neff 1989; Dunlop et al. 1993; McLeod & Rieke 1994), while relatively few studies have been made of the host environment of PHL 909 (see Gehren et al. 1984; Dunlop et al. 1993). The *HST* results will be compared with the previous ground-based results in § 4.3.

2. OBSERVATIONS

The quasars PHL 909 and PG 0052+251 were observed on 1994 October 17 and December 4, respectively, for 1400, 500,

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1996ApJ...457..557B

TABLE 1

CHARACTERISTICS OF HOST GALAXIES OF PHL 909 AND PG 0052+251[a]

Quasar	z	V (QSO)	M_V (QSO)	F606W	M_V	kpc per 1″	Size[b]	Hubble Type
PHL 909	0.171	15.7	−22.9	17.3	−20.9	1.88	1.″4	E4
				(16.8)	(−21.4)			
PG 0052+251	0.155	15.4	−23.0	17.0	−21.1	1.75	1.4	Sb
				(16.8)	(−21.3)			

[a] The upper row for each quasar gives aperture magnitudes between 0.″5 and 10.″0. The lower row gives (in parentheses) the magnitudes computed using a best-fit de Vaucouleurs profile for PHL 909 or an exponential profile for PG 0052+251.
[b] Effective radius for PHL 909 and exponential scale length for PG 0052+251.

and 200 s with the Wide-Field Camera (WF3) of *HST*. All of the exposures were taken with the wide-band visual filter, F606W. The center of light of the quasar PHL 909 was placed 2.″6 from the center of WF3 and the center of light of PG 0052+251 was 4.″9 from the center of WF3. The scale of WF3 is 0.″0996 pixel^{-1}. For further information about the WFPC2, see Burrows (1994), Trauger et al. (1994), and Holtzman et al. (1995a, b). Further details of the observational procedures are given in Paper I and Paper II.

3. RESULTS

In this section, we first discuss in § 3.1 the images of the host galaxies of PHL 909 and PG 0052+251 and then determine their principal quantitative characteristics. Next we present in § 3.2 the positions and apparent magnitudes of the galaxies that are projected relatively close to PHL 909 and PG 0052+251. Finally, we give in § 3.3 the measured apparent magnitudes and projected separations of the ten brightest H II regions in the host galaxy of PG 0052+251.

We report measured F606W magnitudes on the *HST* photometric scale established by Holtzman et al. (1995b). For convenience in comparison with standard galaxy magnitudes, we convert the F606W magnitudes to V-magnitudes using the calculations of k-corrections and the relative sensitivities of different bands calculated by Fukugita, Shimasaku, & Ichikawa (1995). To determine the offsets between V and F606W, we interpolate in redshift between entries in their Table 3 and their Table 6. For an elliptical galaxy at the redshift of PHL 909, we find $V - m(\mathrm{F606W}) = 0.44$ mag. For an Sb galaxy at the redshift of PG 0052+251, we find $V - m(\mathrm{F606W}) = 0.32$ mag. We will use these conversions below when transforming from F606W to V-magnitudes.

None of the major conclusions of this paper are affected significantly by corrections to the inferred V-magnitudes caused by k-corrections, magnitude offsets, and photometric zero-point differences.

Cosmic-ray subtraction and pipeline STScI flat-fielding are the only processing performed on the *HST* images used to construct the seven figures of this paper, except where explicitly stated otherwise. Cosmic-ray removal was a relatively easy task as the three exposures of a given quasar were aligned to an accuracy of better than 0.3 pixels. Cosmic rays were identified by a pixel-by-pixel comparison of pairs of images; the intensity of a pixel containing a cosmic ray was replaced by the scaled value of the intensity of the pixel in the other image.

3.1. *Host Galaxies of PHL 909 and PG 0052+251*

We first present and analyze the images of the host galaxy of PHL 909 (in § 3.1.1) and then discuss the host galaxy of PG 0052+251 (in § 3.1.2). Following the procedure that is frequently used with ground-based observations of quasar hosts, we next discuss (in § 3.1.3) the one-dimensional profiles of both galaxies. Finally, we demonstrate by using different procedures (in § 3.1.4) that the precise way we subtract the stellar PSF does not affect significantly the measured morphology or photometry of the host galaxies. Finally, we summarize (in § 3.1.5) the information that is obtained on the two host galaxies.

3.1.1. *The Host Galaxy of PHL 909*

Figure 1 (Plate 1) displays the environment of PHL 909. The host galaxy of PHL 909 is obvious even in the raw data of the *HST* image.

The upper panel of Figure 2 (Plate 2) presents the short exposures, 500 and 200 s, of PHL 909. The host galaxy is easily visible on the 500 s image and can also be recognized on the shortest exposure, 200 s.

Figure 3 (Plate 3) shows the host galaxy in somewhat more detail since a best-fitting stellar PSF (representing the quasar nucleus) was subtracted from the 1400 s image (see Paper I and Paper II for a description of the PSF and the subtraction procedures). To a limiting surface brightness of $\mu = 24.5$ arcsec^{-2} (used here and in later discussions of PHL 909), the major axis of the host galaxy is 18″ (34 kpc) and the minor axis is 10″ (19 kpc). The position angle of the major axis is 138°. The measured sky brightness in the PHL 909 image was 190 detected photons per pixel in 1400 s, with a standard deviation of 14 photons, which corresponds to a sky brightness of 22.1 mag arcsec^{-2}.

We have performed aperture photometry (between 0.″5 and 10.″0) on the PSF-subtracted image of PHL 909. We find $m(\mathrm{F606W}) = 17.3 \pm 0.3$ and $M_V = -20.9$, which is more than 1 mag fainter than the brightest elliptical galaxies in rich clusters (see Hoessel & Schneider 1985; Postman & Lauer 1995).

The host galaxy of PHL 909 is, at least in its appearance in this F606W image, smooth and relatively featureless, similar to a normal E4 galaxy. Within the inner 1″, the surface brightness of the host galaxy appears to be somewhat higher on one side of the quasar compared to the other side. In addition, there are some arclike features at ~2″ from the center of light of the quasar. We are not able to determine from the available data whether these features are artifacts. A measurement of the surface brightness along the major axis of PHL 909 does not show evidence for a break in the light distribution (upper limit ~0.15 mag) that might be associated with the end of a disk. We therefore tentatively adopt the classification E4. Additional imaging of PHL 909 with *HST* using different filters with the WF3 (to determine the host galaxy colors) and separate exposures with the PC2 (to determine better the innermost structure of the host galaxy), as well as comparable CCD images of classical nearby galaxies, would be useful in making a more definitive classification of the host galaxy.

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1996ApJ...457..557B

3.1.2. *The Host Galaxy of PG 0052+251*

Figure 4 (Plate 4) shows a beautiful spiral galaxy in which the quasar PG 0052+251 apparently resides. Bright H II regions are visible in the spiral arms. The figure displays the 1400 s *HST* image with the cosmic rays removed.

The lower two panels of Figure 2 demonstrate the extraordinary power of the Wide-Field camera for discovering host galaxies of quasars. The host galaxy of PG 0052+251 is easily visible on all three of the *HST* images, including the very short 200 s exposure.

Figure 5 (Plate 5) shows the host galaxy after a best-fit stellar PSF (representing the quasar nucleus) is subtracted from the original image. To a limiting surface brightness of $\mu = 24.8$ mag arcsec^{-2} (used here and in later discussions of PG 0052+251), the major axis of the host galaxy is 18″ (32 kpc) and the minor axis is 12″ (21 kpc). The position angle of the major axis is 173°. The sky brightness in the 1400 s PG 0052+251 image is 22.3 mag arcsec^{-2}.

Comparing the shape of the spiral arms and the rather prominent dust lanes with figures in the Hubble Atlas, we suggest that this host galaxy resembles a normal Sb galaxy. The inclination angle between the plane of the host galaxy and our line of sight is 50° ± 5°.

We have also performed aperture photometry (between 0.″5 and 10.″0) on the PSF-subtracted image of PG 0052+251. We find m(F606W) = 17.0 ± 0.3 and $M_V = -21.1$, which is 0.6 mag brighter than an L^* galaxy in the field (Schechter 1976; Kirshner et al. 1983; Efstathiou, Ellis, & Peterson 1988).

3.1.3. *One-Dimensional Surface Brightness Profiles*

Figure 6 shows the one-dimensional (azimuthally averaged) surface brightness profiles of the host galaxies of PHL 909 and PG 0052+251, as measured on the *HST* images after subtraction of a best-fit stellar PSF (see Figs. 3 and 5). The filled circles show the data and the best-fitting de Vaucouleurs profile is represented by a continuous line. The best-fitting exponential profile is indicated by a dotted line.

The best-fitting de Vaucouleurs profile fits the host galaxy of PHL 909 very well and yields an effective radius of 2.″0. The total de Vaucouleurs magnitude of the host galaxy of PHL 909 is m(F606W) = 16.8, somewhat brighter, as expected, than the measured aperture magnitude of 17.3 ± 0.3 mag. The average surface brightness at the effective radius is $\mu = 21.8 \pm 0.2$ mag arcsec^{-2}. The exponential profile is not a good fit to the light distribution of the host galaxy of PHL 909.

The measured one-dimensional profile of the host galaxy of PG 0052+251 is very interesting. For this spiral host galaxy, the bottom panel of Figure 6 shows that the best-fitting de Vaucouleurs profile fits well the measured surface brightness down to a surface brightness level of about 23 mag arcsec^{-2}. Below 23 mag arcsec^{-2}, the de Vaucouleurs profile falls more rapidly than the measured profile. The exponential disk profile does not reproduce well the measured values in the inner regions, but does fit the measured profile in the outer regions about as well as the de Vaucouleurs profile. These results are consistent with what should be expected, upon reflection, for a spiral galaxy in which the light in the inner regions is dominated by a de Vaucouleurs bulge and the light in the outer regions comes primarily from an exponential disk.

The exponential profile has a scale length of 1.″4 and a total magnitude of m(F606W) = 16.8. The exponential fit has a total magnitude slightly brighter than the aperture magnitude of 17.0 ± 0.3.

We have estimated an apparent magnitude for the bulge component of the host galaxy of PG 0052+251 in the following manner. We subtracted the best-fit exponential surface brightness profile given in Figure 6, which fits the observed light distribution beyond 1″, from the total surface brightness profile and assigned the residual light to a bulge. We find in this way a spheroid magnitude of m(F606W) = 19.9 ± 0.2. The spheroid is about 3.1 mag fainter than the disk, which is consistent with what is known about the disk and spheroid of the Galaxy (see, e.g., Bahcall, Schmidt, & Soneira 1983).

The *HST* images of PG 0052+251 show that one must use caution in interpreting the results of one-dimensional profile fits to the residual light measured after subtracting a stellar

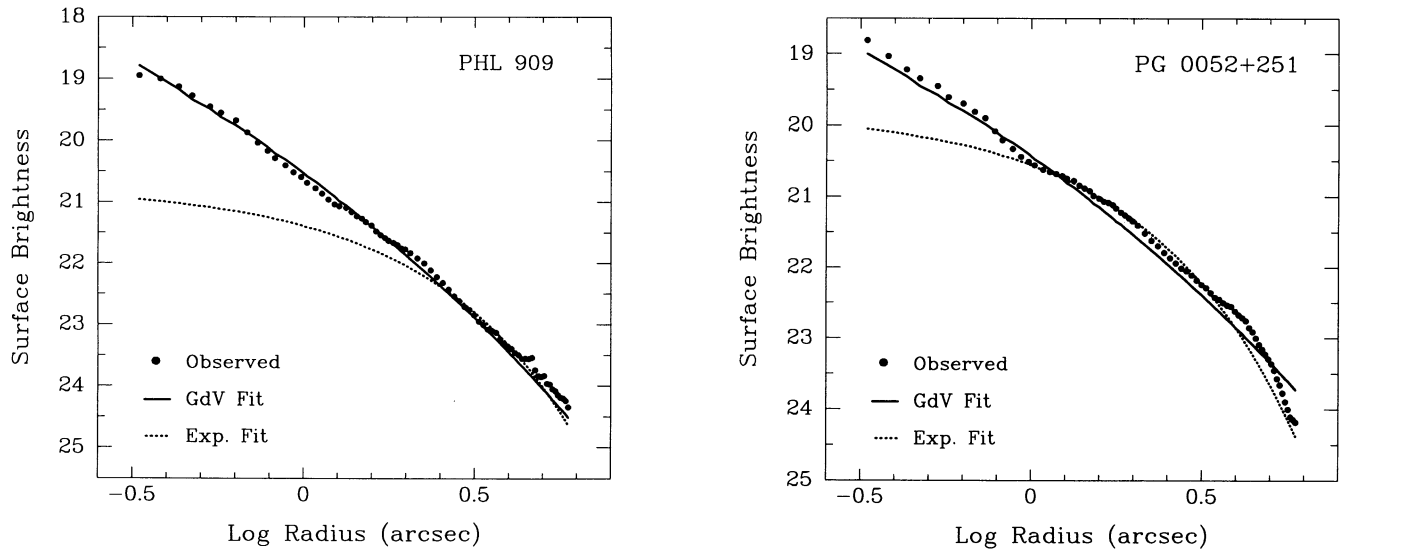

FIG. 6.—Azimuthally averaged profiles of PHL 909 and PG 0052+251. Surface brightness profiles are plotted for the host galaxies vs. the logarithm of the radius in arcsec. The ordinate is the surface brightness measured in F606W mag arcsec^{-2}. The filled circles represent the data and the continuous line show the best-fitting de Vaucouleurs profile. The exponential disk that best fit the data outside of 1″ is represented by a dotted line.

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1996ApJ...457..557B

PSF from a quasar image. Many authors have, working with data obtained from ground-based telescopes, used such studies to infer the morphology of the host galaxies of quasars. However, for the spiral host of PG 0052+251 the bottom panel of Figure 6 shows that a de Vaucouleurs profile fits the measured light distribution as well as an exponential profile.

The parameters derived from the fits to the radial profiles are not sensitive to how the points are weighted. We fit the profiles of PHL 909 and PG 0052+251 using four weighting schemes: uniform, (radius)$^{1/2}$, σ^{-1}, and σ^{-2}, where σ is the uncertainty in the measurements of the individual points. The four derived luminosities for each galaxy varied by only 0.1 mag. The scale length for the PG 0052+251 host changed by less than 0".1 using the various weightings; the scale length for PHL 909 ranged from 1".4 to 2".0.

3.1.4. *Insensitivity to Stellar PSF Subtraction*

How sensitive are the measurements of the morphology and the photometry of the host galaxies to the details of the PSF subtraction of the stellar (nuclear) quasar? In order to answer this question, we have carried out the measurements in different ways and compared the results. Altogether, we measured the characteristics of the host galaxies in three different ways: (1) we subtracted our best stellar PSF from the total image, minimizing the residuals in the diffraction spikes (designated as "Best PSF" in Table 2); (2) we subtracted a much inferior stellar PSF and then repeated the measurements (designated as "Bad PSF"); and (3) we measured the major and minor axes of the host galaxies without subtracting any stellar PSF (designated as "No Subtraction").

The results of these measurements are summarized in Table 2 and described below.

The values obtained by subtracting our best PSF have been presented in the previous discussion of § 3.1; the values obtained are given in Table 2 in the first and fourth rows.

We constructed an alternate PSF from a star image that was taken about five months before, and in a different CCD, than the two quasar images. Moreover, the exposure level of this image was insufficient to accurately determine the outer regions of the PSF. We will refer to this PSF as the "Bad PSF," following the nomenclature of Table 2.

Subtracting the Bad stellar PSF from the image of PHL 909, we found an effective radius of 2".4 (0".4 more than with our best PSF) and a total magnitude of m(F606W) = 16.6 (0.2 mag brighter than obtained with our best PSF subtraction). The major and minor axes measured with the Bad PSF subtraction were 19" and 10", respectively, compared to 18" and 10" with our best PSF. For PG 0052+251, we found with the Bad stellar PSF, an exponential scale length of 1".5 (0".1 more than with our best PSF) and a total magnitude of m(F606W) = 16.8 (in agreement with our best PSF). The major and minor axes measured with the Bad PSF subtraction were 18" and 11", respectively, compared to 18" and 12" with our best PSF. These results are given in rows two and five of Table 2.

For PHL 909, the major axis without PSF subtraction was measured to be 17" compared to 18" with our best stellar PSF subtraction; the minor axis was measured to be 10" without PSF subtraction, which is to be compared to 10" with PSF subtraction. For PG 0052+251, the major and minor axes measured without PSF subtraction were 18" and 11", respectively, compared to 18" and 12" with our best PSF subtraction. These results are presented in rows three and six of Table 2.

We conclude that, within the class of procedures we have considered, the details of the subtraction process are not important for measuring the luminosities or the morphological characteristics of the host galaxies.

3.1.5. *Summary of Host Galaxy Characteristics*

Table 1 summarizes the principal characteristics of the host galaxies of PHL 909 and PG 0052+251, as determined from the *HST* observations. The centers of the galaxies were determined by locating the pixels of given surface brightnesses, fitting ellipses to this distribution, and identifying the center of the galaxy with the center of the ellipse. The uncertainties in the positions of the centers of the galaxies were estimated by the dependence of the ellipse centers with surface brightness. The center of the host galaxy and the center of the quasar nuclear light are coincident for both PHL 909 and PG 0052+251 to within the accuracy with which we can locate the galactic centers. The measurement error for the galactic centers is 0".3 for PG 0052+251 and 0".5 for PHL 909.

3.2. *Galaxies in the Fields of PHL 909 and PG 0052+251*

No very close galactic companions (projected separation less than 3", see Paper II) to PHL 909 are visible in the *HST* images of this quasar. There are two faint stellar images projected close to PG 0052+251, the closest is 4".2 northwest of the quasar nucleus and the more distant is 6".5 south of the quasar nucleus. Their apparent magnitudes are, respectively, 23.6 and 21.3.

Tables 3 and 4 list the aperture magnitudes (apertures of 0".5 to 4".0 as appropriate) of galaxies in the fields of PHL 909 and of PG 0052+251 that are brighter than m(F606W) = 22.5 and that have a projected separation of less than 70 kpc (at the quasar redshift), from the center of light of the quasar. The F606W magnitudes given in Table 4 are typically 0.7 mag brighter than the g-magnitudes given in Kirhakos et al. (1994); within the measurement uncertainties ($\sim$0.3 mag), this is consistent with what would be expected from the filter offsets and k-corrections (see Fukugita et al. 1995).

TABLE 2

DEPENDENCE OF HOST GALAXY PARAMETERS ON POINT-SPREAD FUNCTION SUBTRACTION

Quasar	Procedure	Total Mag (F606W)	Major Axis	Minor Axis	Size[a]
PHL 909	Best PSF	16.8	18"	10"	2".0
PHL 909	Bad PSF	16.6	19	10	2.4
PHL 909	No subtraction	...	17	10	...
PG 0052+251	Best PSF	16.8	18	12	1.4
PG 0052+251	Bad PSF	16.8	18	11	1.5
PG 0052+251	No subtraction	...	18	12	...

[a] Effective radius for PHL 909 and exponential scale length for PG 0052+251.

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1996ApJ...457..557B

TABLE 3

GALAXIES IN PHL 909 FIELD

Galaxy	m(F606W)	d	d (kpc)	$\Delta\alpha$	$\Delta\delta$
A.....	21.4	12″.5	23.5	1″.4	−12″.4
B.....	20.5	15.9	30.0	−15.5	3.7
C.....	19.6	17.8	33.5	8.0	15.9
D.....	19.6	19.6	36.8	12.2	−15.3
E.....	20.4	20.0	37.5	−7.0	−18.7
F.....	18.5	28.2	53.1	−1.5	−28.2
G.....	22.2	28.4	53.4	−28.4	1.2
H.....	18.5	30.6	57.5	30.4	−3.2
I.....	21.9	31.7	59.7	−31.6	3.0
J.....	22.2	36.4	68.5	−30.9	20.1

TABLE 4

GALAXIES IN PG 0052+251 FIELD

Galaxy	m(F606W)	d	d (kpc)	$\Delta\alpha$	$\Delta\delta$
A.....	18.8	14″.0	24.6	3″.5	−13″.6
B.....	19.5	18.5	32.4	1.8	18.4
C.....	20.9	22.9	40.0	−5.9	22.1
D.....	18.2	27.1	47.3	26.4	5.9
E.....	21.2	27.3	47.8	−6.7	−26.5
F.....	21.9	32.2	56.3	−13.3	−29.3
G.....	<20.2	39.1	68.5	−33.4	−20.4

It would be useful to obtain redshifts for these galaxies. When the galaxy redshifts are available, one can investigate the extent of the galactic halos with *HST* ultraviolet absorption-line spectra of the quasars.

It is possible that one or more of the galaxies listed in Tables 3 or 4 is associated with either PHL 909 or PG 0052+251. With our definition of aperture magnitudes, the average density of galaxies brighter than 22.5 mag in the four CCDs in which the quasars do not appear is 7×10^3 galaxies per square degree. For consistency, we consider galaxies that are within the same separation, 25 kpc, from the quasar centers of light as was adopted in the discussion of companion galaxies in Paper II. With this observed average density of galaxies, there is a 9% chance that by accident there would be, as observed, two galaxies that are projected within 25 kpc of the quasar centers of light.[2] (This estimate of the probability may be somewhat of an overestimate since the average galaxy density in the four CCDs in which quasars do not appear may be enhanced over the field density.)

3.3. *The Brightest* H II *Regions in the Host Galaxy of PG 0052+251*

Figure 7 (Plate 6) shows the 11 brightest H II regions that we have found in the host galaxy of PG 0052+251. The measured apparent magnitudes of these H II regions range from m(F606W) = 22.9 to m(F606W) = 24.9. The brightest H II region is marked as "j" in Figure 7 and is discussed in § 4.4.

Table 5 presents the measured characteristics of the H II regions shown in Figure 7, including the apparent magnitudes, the distance, d, in arcseconds of the H II region from the quasar nucleus, and the offsets in right ascension and declination between each H II region and the quasar nucleus. The aperture magnitudes given in Table 5 were measured with apertures of 0″.3–1″; the typical magnitude uncertainties are ±0.3 mag but are somewhat larger for those regions with $d < 1''.4$.

4. DISCUSSION

In this section, we summarize in § 4.1 the conclusions about host galaxies of luminous quasars that follow from the analyses of *HST* images studied in this paper and in previous papers in this series. We describe in § 4.2 how the detection of the host galaxies of PHL 909 and PG 0052+251 validates the techniques we have used in analyzing *HST* observations. Next we compare in § 4.3 the *HST* results with previous ground-based studies of PHL 909 and PG 0052+251. Then, we discuss in § 4.4 the H II regions that are found in the spiral arms of PG 0052+251 and stress the importance of studying these regions spectroscopically. Finally, we point out in § 4.5 that it may be feasible to obtain a direct upper limit on the mass of the nuclear region of PG 0052+251 by measuring a rotation curve for the host galaxy.

4.1. *What Can We Conclude About the Host Galaxies of Luminous Quasars?*

The principal conclusion from the results presented in this and in the previous papers in this series (Papers I–IV) is that luminous quasars exist in a variety of environments. There are quasars for which no definitive evidence for host galaxies is seen to the limit of the sensitivity obtained so far, which is typically of order L^* [$M_V(L^*) = -20.5$], or a magnitude fainter, where L^* is the characteristic Schechter magnitude of field galaxies (Kirshner et al. 1983; Efstathiou et al. 1988). Examples of quasars in this category include (see Papers I and II) PG 0953+414, PG 1202+281, PKS 1302−102, PG 1307+085, and 3C 323.1. There are also two quasars in which host elliptical galaxies are clearly detected, namely, 3C 273 (Paper II) and PHL 909. Finally, PG 0052+251 exists in a spiral galaxy and PKS 2349−014 is embedded in a complex environment, including a large, off-center nebulosity and thin (possibly tidal) wisps (see Paper III).

In the sample of luminous quasars that we have studied, radio-quiet and radio-loud quasars are not uniquely distinguished by their host galaxies. There are both radio-loud (e.g., PKS 1302−102, and 3C 323.1) and radio-quiet (e.g., PG 0953+414 and PG 1202+281) quasars for which we have not

TABLE 5

H II REGIONS IN THE HOST GALAXY OF PG 0052+251

Region	m(F606W)	d	$\Delta\alpha$	$\Delta\delta$
a.....	23.7	1″.3	0″.9	0″.9
b.....	23.5	1.3	1.3	−0.3
c.....	23.8	1.3	−0.9	−0.9
d.....	23.3	1.4	−1.3	0.5
e.....	23.9	1.7	−0.6	−1.6
f.....	24.2	3.1	3.1	0.4
g.....	24.7	3.3	3.2	−0.7
h.....	24.5	3.8	2.2	−3.1
i.....	24.9	3.9	1.6	3.6
j.....	22.9	4.1	3.0	−2.8
k.....	24.6	4.3	1.9	3.8

[2] After this paper was accepted for publication, we were informed by T. Boroson of an important observing project by T. Boroson, J. Dunlop, and D. Hughes in which they have obtained redshifts for two of the galaxies in the PHL 909 field (see Table 3). For galaxy C they find (Boroson 1995) $z = 0.102$, and for galaxy F they find $z = 0.169$.

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1996ApJ...457..557B

detected the host galaxies and there is both a radio-quiet (PHL 909) and a radio-loud (3C 273) quasar for which we have detected a host elliptical galaxy.[3]

Do all luminous quasars reside in luminous galaxies? No, the results presented here for PHL 909 and PG 0052+251 provide further evidence supporting the conclusion stated in Papers I and II that some luminous nearby quasars do not reside in particularly luminous galaxies. We easily see moderately bright host galaxies for PHL 909 and PG 0052+251 with the same exposures that do not reveal any host galaxies for other quasars with similar nuclear properties. For example, PG 1202+281 (studied in Papers I and II) has a redshift $z = 0.165$, similar to (and intermediate between) the redshift of PHL 909 ($z = 0.171$) and the redshift of PG 0052+251 ($z = 0.155$). Also, the apparent magnitude of the quasar nucleus is similar for PG 1202+281 ($V = 15.6$) and for PHL 909 ($V = 15.7$) and PG 0052+251 ($V = 15.4$). The host galaxies ($M_V \sim -21$) for PHL 909 and for PG 0052+251 are visible on the *HST* images with no special data processing, whereas we could not detect any convincing evidence for a host galaxy on similar *HST* images of PG 1202+281. The upper limit on the brightness of a model spiral host galaxy (similar in morphology to that seen in PG 0052+251) was set at $M_V = -19.6$ in Paper II.

Of course, the quasars for which we have not yet detected host galaxies may reside in fainter galaxies. We showed in Paper II, for example, that our results on the first eight quasars we studied were consistent with the host galaxies being described by a Schechter luminosity function, provided that the cutoff at faint luminosities was at least as faint as $0.5L^*$.

The ultraviolet "big bump" that appears in many quasar spectra has been suggested to be a signature of thermal radiation from the accretion disk around a central black hole (Malkan 1983). It is of interest that the two elliptical host galaxies that we have detected correspond to very different types of "big bumps." PHL 909 has the weakest bump in the sample of McDowell et al. (1989) and 3C 273 has one of the strongest ultraviolet bumps.

4.2. *Validation of the Analysis Techniques: PHL 909 and PG 0052+251*

There is an old adage: "The proof of the pudding is the eating." The validation of the techniques that we have used is the detection of the host galaxies of PHL 909 and PG 0052+251PH and the measurement of their properties. For faint very extended nebulosity, the validation of the technique is in the detection of the emission around PKS 2349−014 (see Paper III).

The short, 200 s, exposures provide an empirical calibration for the detectability of host spiral or elliptical galaxies in the 7 times longer exposures (1400 s) of eight quasars studied with similar techniques (see Paper II). The relative increase in sensitivity is bounded by two extremes: (1) read-noise limit (2.1 mag increase in sensitivity), and (2) sky-noise limit (1.05 mag increase in sensitivity). The sky noise approximately equals the readout noise in the 200 s exposures in this filter, so the limiting sensitivity for host galaxies in 1400 s is about 1.4 mag fainter than the absolute magnitudes measured in this paper for the host galaxies of PHL 909 and PG 0052+2251. These estimates must be modified somewhat by the fact that the host galaxies of PHL 909 and PG 0052+251 are well above the detection thresholds on the 200 s exposure, which is perhaps compensated for by the fact that we have neglected additional saturated pixels and scattering that are produced by the quasar nucleus in the longer exposures. We conclude that host galaxies like PHL 909 and PG 0052+251 could be detected to a limiting magnitude of about $M_V = -20.0 \pm 0.5$ on 1400s exposures. This value is in good agreement with the estimates of our limiting sensitivity determined from simulations in Paper II.

We have shown in § 3.1.4 and in Table 2 that the inferred characteristics of the host galaxies of PHL 909 and PG 0052+251 are insensitive to the details of the different procedures that we use to subtract a stellar PSF from the *HST* images. The difference in the host galaxy magnitudes derived using our Best PSF and a Bad PSF is 0.2 mag for PHL 909 and 0.0 mag for PG 0052+251. The measured major and minor axes are the same, to 10% or better, for PHL 909 and PG 0052+251, independent of whether the measurements are made with the Best PSF, the Bad PSF, or no subtraction at all. These tests reinforce the result obtained in Paper II, where we showed that we obtained the same apparent magnitudes (to an accuracy of ±0.17 mag) for model host galaxies that were fitted to the observations in two very different ways. In Paper II, we minimized the residuals in the fits by either using all of the emission in annuli centered on the quasar images (the common practice in analyzing ground-based observations) or by first matching as well as possible the diffraction spikes in the quasar and the stellar images.

4.3. *Comparison with Ground-Based Studies*

The lower panel of Figure 6 shows that a de Vaucouleurs profile provides an excellent fit to the azimuthally averaged light distribution of the host spiral galaxy of PG 0052+251 over a large range in angular distance, from 0.″3 to about 5.″0. Over this angular range, the observed surface brightness varies by more than 4.5 mag. In fact, the de Vaucouleurs fit to the azimuthally averaged light distribution is a better fit than the exponential disk model over nearly all the measured range (see Fig. 6). The full two-dimensional light distribution is required to see that the host of PG 0052+251 is a spiral, not an elliptical, galaxy.

Since it has been standard practice to infer the morphological type of host galaxies of quasars from azimuthally averaged ground-based observations, the results shown in the lower panel of Figure 6 suggest that the inferences regarding the morphological types of host galaxies based upon azimuthally averaged profiles should be reexamined.

The host galaxy of PG 0052+251 has been the subject of several previous ground-based studies. The first such study for PG 0052+251 of which we are aware is a spectroscopic investigation by Boroson et al. (1982), who concluded from measurements of the nebulosity surrounding the stellar source that the host was probably a spiral galaxy with (for our choice of H_0) $M_V = -20.5$; this result is in satisfactory agreement with our *HST* aperture magnitude of $M_V = -21.1$. From near-infrared ground-based observations, McLeod & Rieke (1994) estimated an H-band magnitude for the host galaxy: $M_H = -24.0$. This result is in good agreement with our measured

[3] It is an interesting and instructive historical exercise to try to trace the early development of the consensus view, based upon ground-based observations, that radio-quiet quasars are in spiral galaxies and radio-loud quasars are in elliptical galaxies. The motivating analogy may have been that Seyfert galaxies are predominantly early-type spirals and strong radio galaxies are predominantly ellipticals. Landmark studies include Sandage (1972), Balick & Heckman (1982), Malkan et al. (1984), and Malkan (1984).

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1996ApJ...457..557B

absolute magnitude at V, if we adopt a typical value of $V-H$ that applies for ordinary galaxies ($V-H \sim 3$, see McLeod & Rieke 1994).

There has been relatively little ground-based imaging of PHL 909. Gehren et al. (1984) estimated an r-band absolute magnitude for the host galaxy of $M_r = -21.5$, which is consistent with our measurement of $M_V = -21.4$. In addition, Gehren et al. suggest the presence of diffuse emission indicating a tidal interaction with galaxy B of Figure 1. Dunlop et al. (1993) performed K-band observations and suggest a bright host galaxy, $M_K = -24.2$, which is consistent with our measurement if $V-K \gtrsim +3$ mag. With regard to morphology, Dunlop et al. propose that the host of PHL 909 may extend toward Galaxy B. The *HST* images show (see Fig. 1) that the quasar and Galaxy B are not connected by diffuse emission that is detectable in our relatively deep exposures (limiting surface brightness of about 25 mag arcsec^{-2}). It is possible that the proximity of the two bright sources, PHL 909 and Galaxy B, on the ground-based images may—because of limited angular resolution—have given rise to a misleading impression of tidally connected emission.

As a further indication of the kind of difficulty that may face ground-based imaging of some quasar hosts, we note that Hutchings et al. (1989) also detected (in deep B and R images) the bright region "j" (see Fig. 7), but suggested that it was a secondary nucleus of the quasar. They also suggested that the bright stellar object about 6".5 southeast of the quasar (see Fig. 5) was a third quasar nucleus. Dunlop et al. (1993), observing in the K band, detected the stellar image and concluded, in agreement with the Hutchings et al. suggestion, that it was a secondary nucleus linked to the quasar. The *HST* data confirm the existence of emission at the locations found by Hutchings et al. and Dunlop et al. Given the location of object "j" within a spiral arm of PG 0052+251 and the morphology of the host galaxy as seen in the *HST* images (see Fig. 5), we conclude that the object "j" is almost certainly an H II region and not a secondary quasar nucleus. The bright stellar object 6".5 southeast of the quasar is almost certainly a star and not another quasar nucleus. On the *HST* images, this object has the light profile of a star and is well separated from the quasar nucleus.

4.4. *The* H II *Regions of PG 0025+251*

The discovery of bright H II regions in the spiral arms of the host galaxy of PG 0052+251 makes possible important new observations. For example, the region marked "j" in Figure 7 has m(F606W) $\approx$ 22.9 and is at a projected distance of about 4".1 from the quasar nucleus; it should be possible to obtain a good spectrum of this H II region with a large ground-based telescope. Stockton & MacKenty (1987) have already shown by narrowband imaging in the [O III] λ15007 line that the H II region "j" has a luminous flux in the 30 Å bandpass centered on redshifted 5007 Å.

It would be of great interest to obtain spectra for as many of the H II regions as possible and to measure their element abundances. This information might provide significant clues to the history and nature of the system in which the luminous AGN PG 0052+251 resides. The relative velocities of the H II regions could also provide valuable information about the dynamics of the host system.

The H II regions also make possible direct tests of the cosmological hypothesis that the quasar and the host galaxy are both at the distance indicated by the quasar redshift. According to this hypothesis, the emission lines in the H II regions should be redshifted by z(H II) = 0.155.

In principle, the apparent magnitudes of the brightest H II regions in the host galaxy of PG 0052+251 can also be used to test whether the galaxy is at the same redshift as the quasar. The broadband measurements of H II regions by Wray & de Vaucouleurs (1980) are potentially useful for this purpose. In practice, using magnitudes of the H II regions in just one color to say something about the distance to PG 0052+251 involves large uncertainties because we do not know the $B-V$ color of the host galaxy, the intrinsic reddening of the host galaxy, the $B-V$ colors of the H II regions, and the total absolute magnitude of host galaxy. Moreover, the *HST* filter is different from the traditional V filter used by Wray & de Vaucouleurs and the emission lines of the H II regions in the host galaxy of PG 0052+251 are redshifted to longer wavelengths than they are in the calibration made using nearby galaxies. We also do not know whether the distribution of H II absolute magnitudes is affected by the presence of the quasar nucleus. If we nevertheless make a crude, preliminary estimate based upon the data of Wray and de Vaucouleurs and the data presented in the present paper, ignoring everything we do not know, we find that the H II regions in PG 0052+251 are about a magnitude brighter than would be expected on the basis of this oversimplified calculation.

4.5. *A Rotation Curve for PG 0052+251?*

Finally, we note that it is possible to obtain a rotation curve for the host galaxy of PG 0052+251. The host galaxy is bright enough, $V \sim 17.0$, that a good spectrum could be obtained with *HST* and perhaps even with a ground-based telescope in excellent seeing. One would expect on the basis of general phenomenological arguments (see, e.g., Malkan 1983; Rees 1984; Wandel 1991) that a black hole in the center of PG 0052+251 would have a mass of order $10^9\ M_\odot$ or less, which is less than the expected mass of the stars and gas in the inner several kpc of the host spiral galaxy. Nevertheless, the rotation curve would set a direct upper limit on the mass of the quasar nucleus, a quantity of fundamental interest.

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1996ApJ...457..557B

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1996ApJ...457..557B

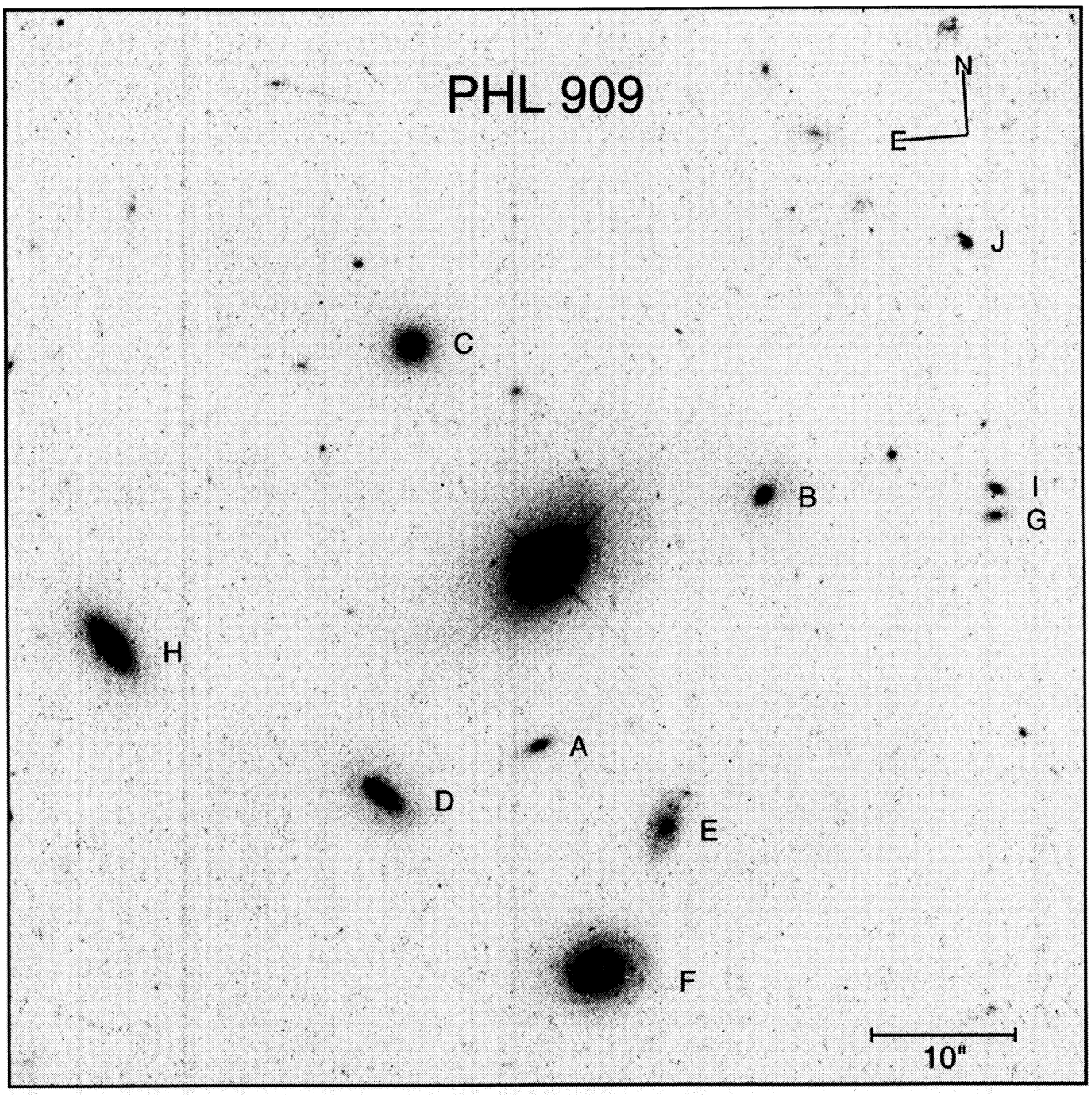

FIG. 1.—PHL 909 and its environment. The candidate companion galaxies within 70 kpc from the center of light of the quasar that are brighter than m(F606W) = 22.5 are labeled "A–J." This image and all the other figures, except Fig. 2, shown in this paper were obtained with a 1400 s exposure using the *HST* WF3 and the F606W filter.

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1996ApJ...457..557B

PLATE 2

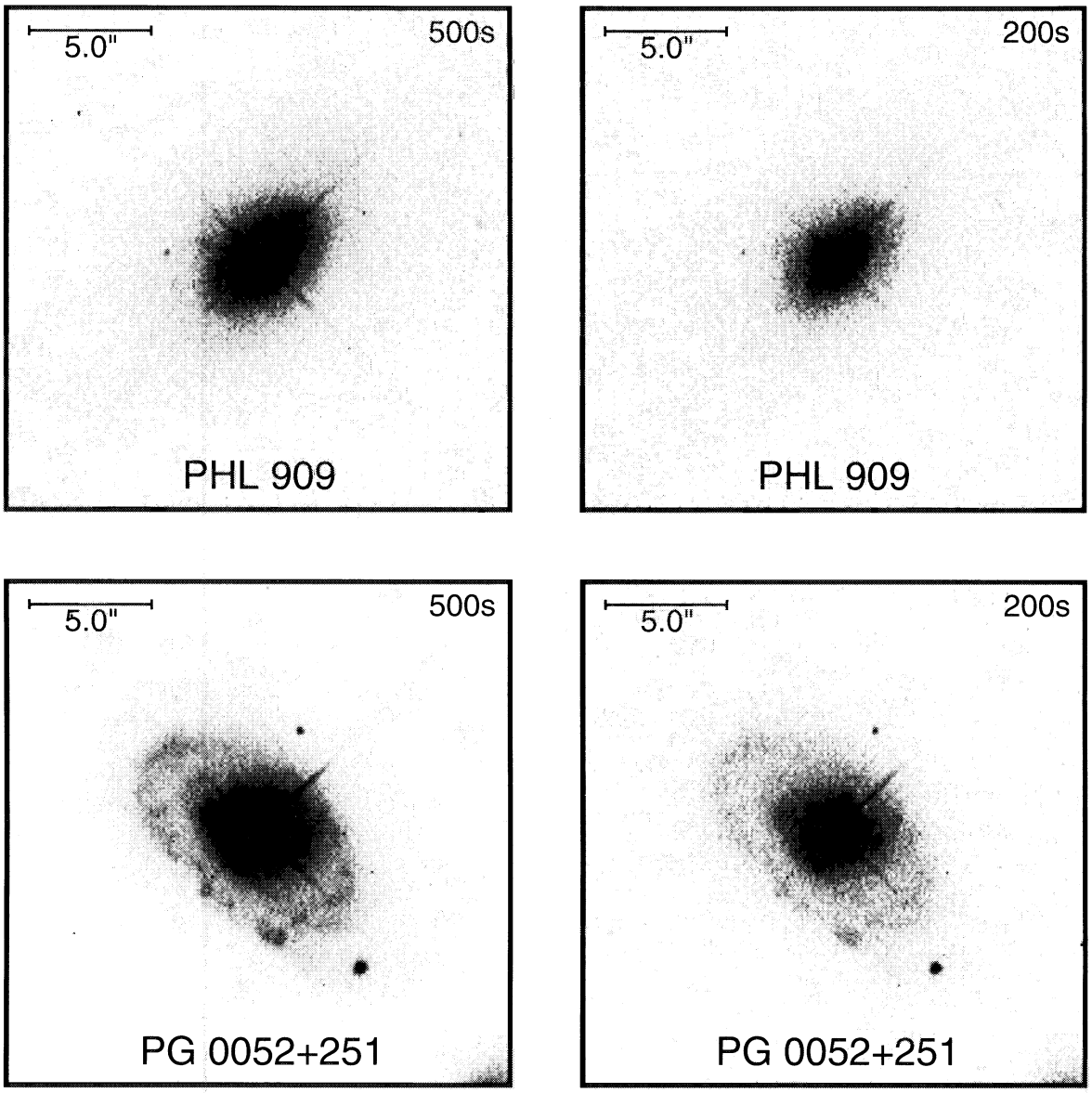

FIG. 2.—Short WF3 exposures of PHL 909 and PG 0052+251. The upper panels show 500 and 200 s images with F606W and WF3 of PHL 909; the lower panels show 500 and 200 s exposures of PG 0052+251. The spiral host galaxy of PG 0052+251 is easily seen on both the 500 and 200 s exposures. The early-type host of PHL 909 is clearly seen on the 500 s exposure and, after the fact, can be recognized on the 200 s exposure. The only image processing performed on these short images was cosmic-ray subtraction and pipeline STScI flat-fielding.

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1996ApJ...457..557B

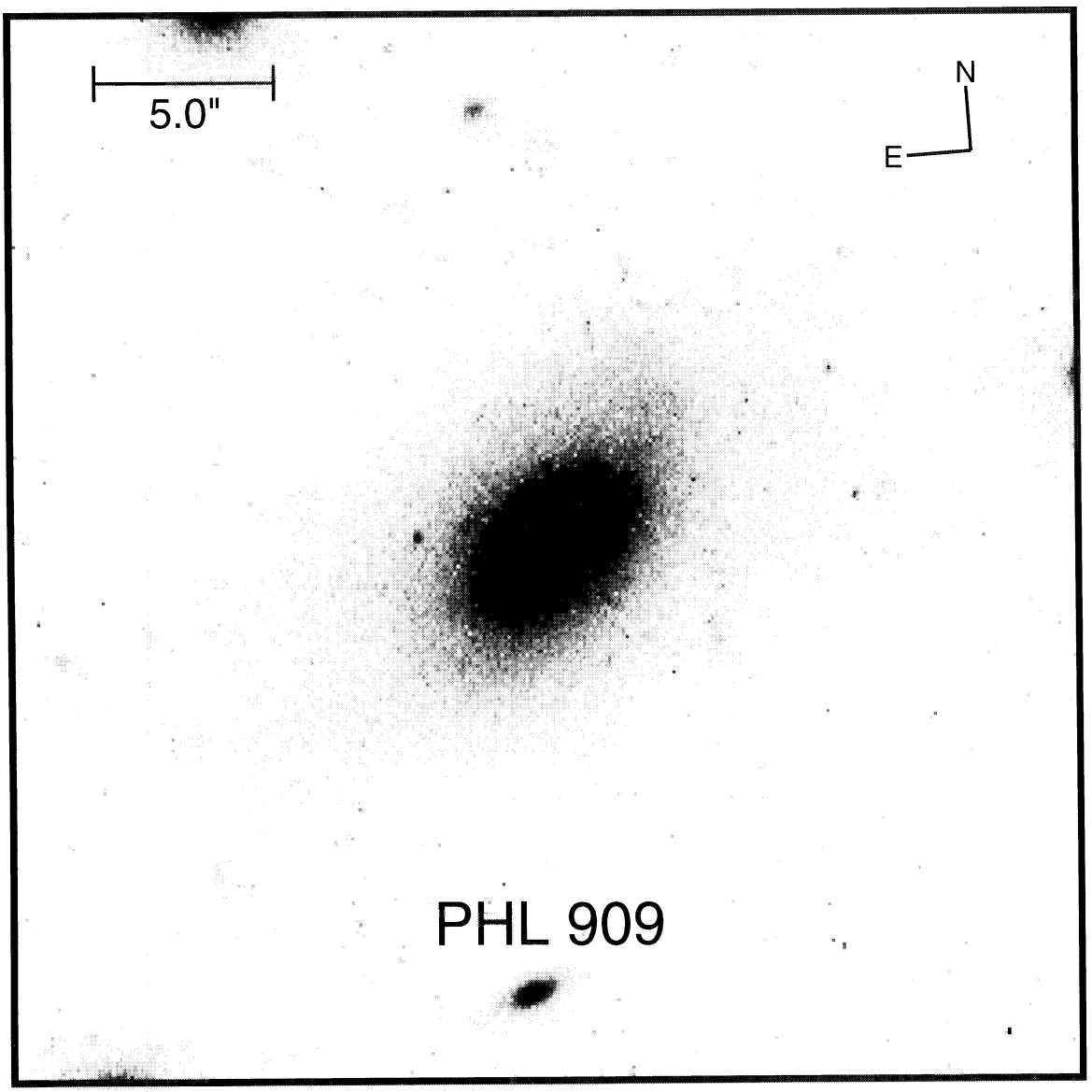

FIG. 3.—Host galaxy of PHL 909. This figure shows the host galaxy of the quasar PHL 909 after a best-fit stellar PSF was subtracted from the original image that is shown in Fig. 1. For this figure, and for Fig. 5, the values of the saturated pixels in the very center of the quasar image were replaced by the average value of the neighboring pixels for cosmetic purposes.

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1996ApJ...457..557B

PLATE 4

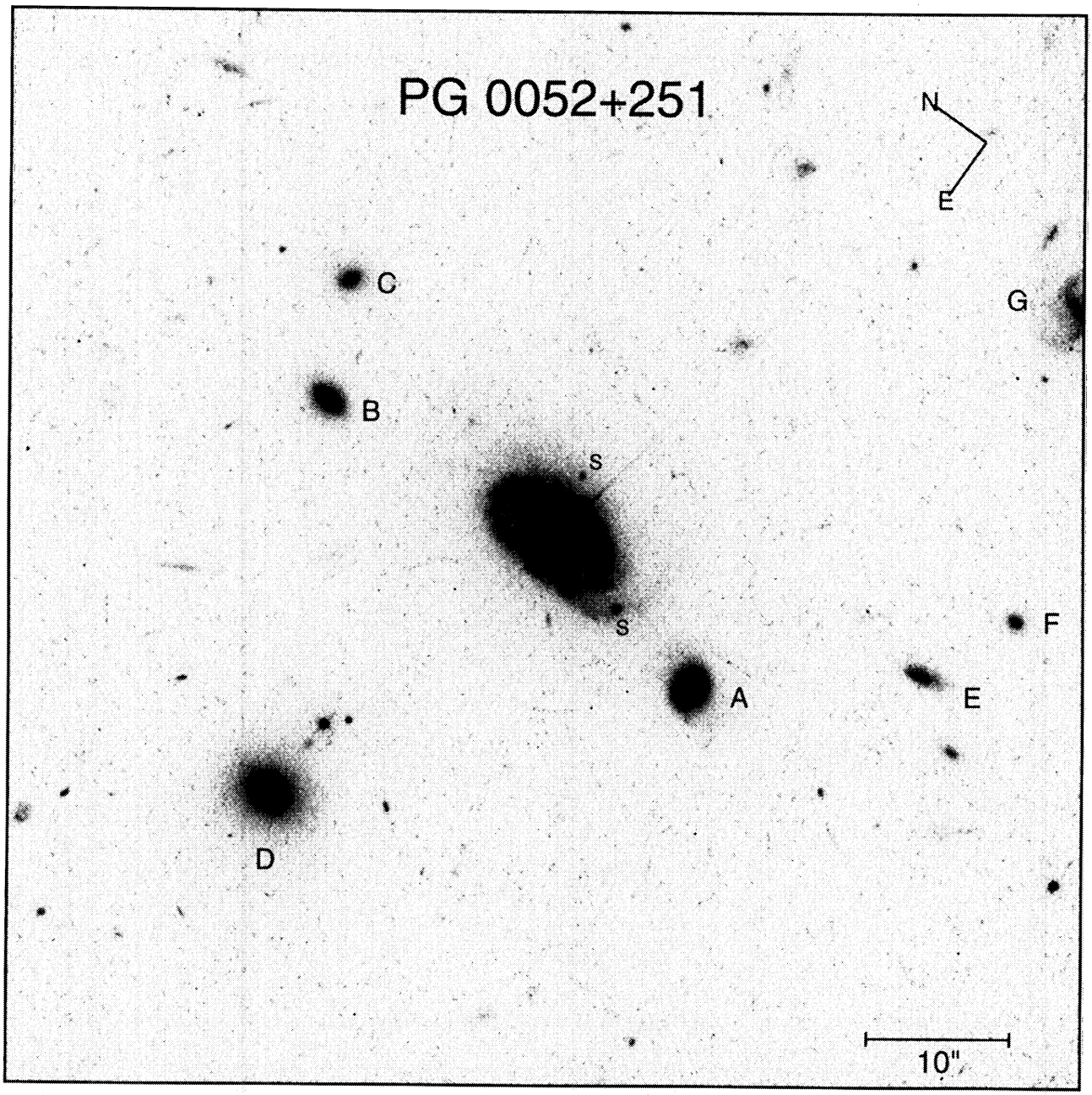

FIG. 4.—PG 0052+251 and its galaxy environment. The candidate companion galaxies within 70 kpc from the center of light of the quasar that are brighter than m(F606W) = 22.5 are labeled "A–G." Two foreground stars are identified by "s."

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1996ApJ...457..557B

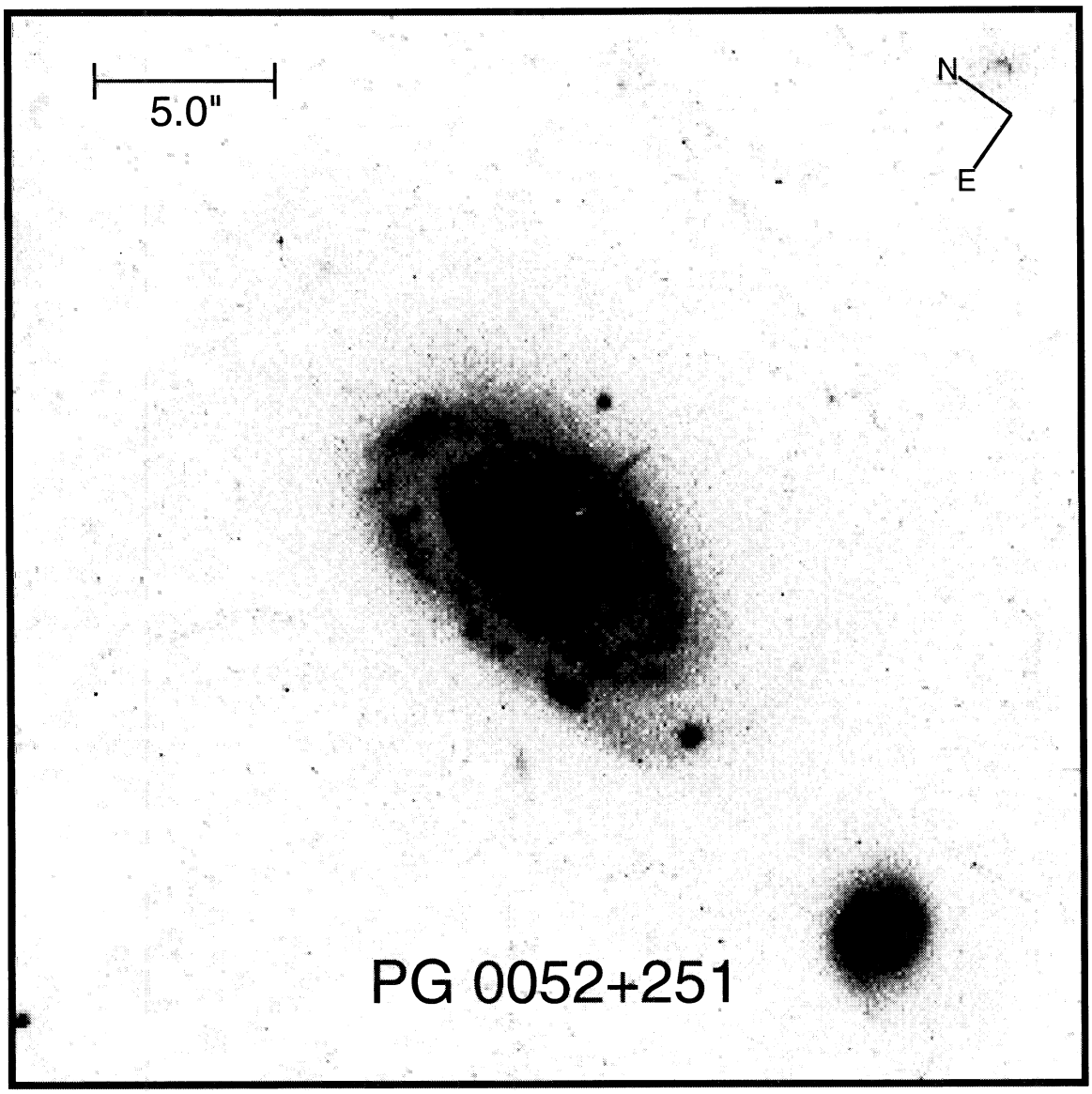

FIG. 5.—Host galaxy of PG 0052+251. This figure shows the host galaxy of the quasar PG 0052+251 after a best-fit stellar PSF was subtracted from the original image that is shown in Fig. 4.

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1996ApJ...457..557B

PLATE 6

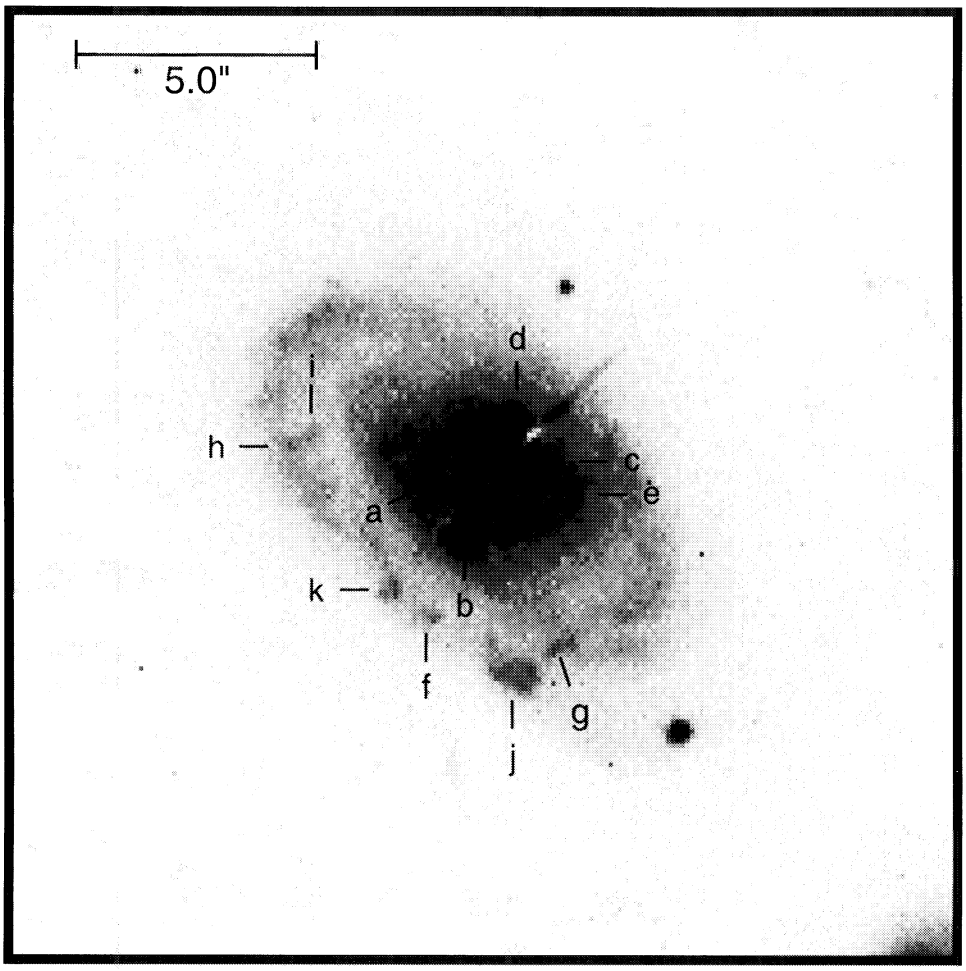

FIG. 7.—H II regions of PG 0052 + 251. Prominent H II regions are labeled "a–k."

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