MARKARIAN 421'S UNUSUAL SATELLITE GALAXY

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ABSTRACT

We present Hubble Space Telescope (HST) imagery and photometry of the active galaxy Markarian 421 and its companion galaxy 14° to the east-northeast. The HST images indicate that the companion is a morphological spiral rather than elliptical, as previous ground-based imaging has concluded. The companion has a bright, compact nucleus, appearing unresolved in the HST images. This is suggestive of Seyfert activity, or possibly a highly luminous compact star cluster. We also report the results of high dynamic range long-slit spectroscopy with the slit placed to extend across both galaxies and nuclei. We detect no emission lines in the companion nucleus, though there is evidence for recent star formation. Velocities derived from a number of absorption lines visible in both galaxies indicate that the two systems are probably tidally bound and thus in close physical proximity. Using the measured relative velocities, we derive a lower limit on the Mrk 421 mass within the companion orbit (R ~ 10 kpc) of 5.9 × 10¹¹ solar masses, and a mass-to-light ratio of >17. Our spectroscopy also shows for the first time the presence of H_α and [N_II] emission lines from the nucleus of Mrk 421, providing another example of the appearance of new emission features in the previously featureless spectrum of a classical BL Lac object. We see both broad and narrow line emission, with a velocity dispersion of several thousand kilometers per second evident in the broad lines.

Key words: BL Lacertae objects: individual (Markarian 421) — galaxies: binary — galaxies: interactions

1. INTRODUCTION

Markarian 421 is a giant elliptical galaxy that contains one of the nearest BL Lac objects, at a redshift of 0.0308 (Ulrich et al. 1975). This object is among the most intensively studied of all active galactic nuclei (AGNs). Mrk 421 is a strong centimeter-wavelength radio source that has shown reported superluminal motion in its compact radio jet (Zhang & Baath 1990), although recent measurements (Piner et al. 1999) do not confirm this. It is optically highly variable in both intensity and polarization. It is seen in X-rays (Comastri et al. 1997), GeV gamma rays (Mukherjee et al. 1997), and up to multi–TeV energies (Krennrich et al. 1997). Episodes of rapid variability have been seen repeatedly at many wavelengths (Tozti et al. 1998; Gaidos et al. 1996), strengthening the evidence for the presence of a compact object as the source of the nuclear activity.

The host galaxy of Mrk 421 has been the subject of several spectroscopic and photometric studies. The first such study (Ulrich et al. 1975) established the redshift based on weak stellar absorption lines, and it also noted that a nearby galaxy 14° to the east-northeast had a similar redshift (z = 0.0316), indicating that it was probably physically related, although, if the velocity difference were due to the Hubble flow, the distance could be a few megaparsecs or more. The companion galaxy was classified as a normal elliptical (Hickson et al. 1982). Further work by Ulrich (1978) showed that Mrk 421 was the brightest member of a group of five to seven galaxies of similar redshift spread over a region of sky of order 10° in radius. The presence of this group increases the likelihood that the companion's proximity to Mrk 421 is physical rather than a random alignment.

There is mounting evidence that AGN phenomena appear to be associated with galaxy mergers or encounters (see Shlosman, Begelman, & Frank 1990; Hernquist & Mihos 1995). In the case of BL Lac objects, a significant number have been found in the last decade or so to be associated with close companions or groups of nearby galaxies (see Falomo 1996; Heidt 1999), although Mrk 421 has apparently been overlooked in this regard. Intrigued by the proximity of these two galaxies, we have analyzed archival HST imagery of the system and performed Hale 5 m long-slit spectroscopic observations aimed at clarifying this association.

Our goal was to understand the nature of the nearby galaxy in relation to Mrk 421 and to investigate the properties of the companion galaxy itself. If the galaxy is as close to Mrk 421 as its projected distance (∼ 10 kpc) suggests, it is deep within the gravitational potential well of Mrk 421, and it is probably sweeping through its stellar halo. The conditions under which such an encounter can take place are of general interest in the understanding of galaxy evolution. Our results will show that the companion galaxy contains a Seyfert-like nucleus and is likely to be tidally interacting with Mrk 421. Although the evidence is circumstantial, this association does appear to lend weight to the suggestions that galaxy encounters are an important factor in AGN evolution and that close companions are associated in some way with the BL Lac phenomenon.

In the following section we summarize the imagery and photometry that indicate nuclear activity in the companion galaxy. Section 3 summarizes the spectroscopic results, from which we derive a velocity profile that indicates a system that is tidally bound. Section 4 presents some further analysis of the spectroscopic results, including a derived lower limit of the bulge mass and mass-to-light ratio of Mrk 421 under some plausible assumptions. Section 5 summarizes and concludes the article.
2. OBSERVATIONS

A log of the observations presented here is shown in Table 1. In the work of Ulrich (1978), the system 14" to the east-northeast of Mrk 421 was denoted as galaxy number 5 of the group of galaxies associated with Mrk 421. Although the galaxy had been noticed prior to this work, it appears that Ulrich was the first to provide a designation for it. Thus we will refer to it in this present work as Mrk 421-5.

We note that users of NASA’s Extragalactic Database (NED) may find a reference to this object as RX J104.4+3812: [BEV98] 014. However, since this reference is only used to distinguish objects within the ROSAT error circle for Mrk 421 and the object is previously known, we prefer the designation given by Ulrich (1978).

2.1. HST Imagery and Photometry

2.1.1. HST Images

Mrk 421 was observed with the HST wide field/planetary camera (WF/PC2) on 1997 March 5, using the F702W filter. Five exposures, one of duration 2 s, two of duration 30 s, and two of duration 120 s were made. The images were prepared by standard techniques described in Holtzman et al. (1995), and the moderate cosmic-ray contamination of the frames was repaired by hand using linear interpolation. In the 2 s exposure, the Mrk 421 nucleus is not saturated, but the companion galaxy is underexposed. The remaining two images overexpose the AGN, but for both Mrk 421’s host galaxy and the companion galaxy the exposures provide good signal-to-noise ratios over the sky background. The pixel scale in these images is 0.0455 pixel⁻¹, and the resolution of HST at the mean filter wavelength (690 nm) is approximately 0.080; thus the images are sampled just slightly under the Nyquist frequency.

Secondary corrections, including those associated with the known gradient in charge transfer efficiency and the pixel area variation across the frame (Holtzman et al. 1995), are not corrected for in the displayed images, but we have applied corrections for these effects in the relative photometry presented in the next section.

Mrk 421 was again observed with WF/PC2 on 1999 May 24 with both the F555W and F814W filters in snapshot mode, with 300 s exposures in each case. Since these were single frame integrations, the cosmic-ray removal for presentation purposes is more difficult, and the images do not add significantly to the structure seen in the F702W image.

Thus we do not present these as part of the imagery here, although in the following section we do include results of the photometry performed on these additional images.

Figure 1 shows a slightly smoothed gray scale of the summed F702W image, with a logarithmic stretch and quantized levels chosen to show the details of the host galaxy of Mrk 421 and Mrk 421-5. Several features of Mrk 421-5 are evident even from this image. First, its structure is not a simple elliptical. A suggestion of spiral arms is evident, and possible evidence of barlike structure appears at the outer edges of the galaxy. Second, the nucleus of the companion is clearly brightened relative to the galactic bulge, as is shown in the inset frame. Third, there is no evidence for any obvious dust lanes or similar absorption features in either the outer or bulge regions of the galaxy.

Figures 2 and 3 illustrate these features. In Figure 2 we show more quantitative evidence for the presence of spiral structure, since the structure is difficult to reproduce adequately in paper copies of the images themselves. Figure 2a is a contour plot centered on the companion galaxy showing structure that is suggestive of spiral arms. In Figure 2b we show centroids of the surface brightness distributions in slices along the galaxy major axis (dashed line) in Figure 2a. The displacement of the brightness centroids clearly shows the presence of spiral structure. (The amplitude of the centroid displacement does not directly track the location of the arms, since it depends on the brightness of the arm structure relative to the surrounding disk.)

In Figure 3 we show a profile of relative surface photometry using the F702W filter along the major axis of the companion galaxy. We have averaged the surface brightness in opposite ±15° sectors and have performed one-dimensional fits to three components that are apparent in the image: an unresolved core, a bulge component (here represented by a Gaussian), and an exponential disk. We have not truncated the disk at an inner radius here; our goal is primarily to show that the data are not consistent with a single power law or other one-parameter models for radial brightness, but are reasonably well modeled by the standard parameters of a disk system.

2.1.2. HST Photometry

We estimated photometric parameters from the HST images using the prescription given by Holtzman et al. 1995, including all of the relevant corrections. We have also transformed the resulting magnitudes to Cousins VRI magnitudes, using the transformations in Holtzman et al. We also include the transformed colors, although we note that the V and I measurements were not contemporaneous with the R measurements. In Table 2 we summarize the results for the nuclear magnitudes of the two galaxies, and the annular bulge magnitude of Mrk 421-5. We have also converted the measured magnitudes to absolute magnitudes using h = 0.65, for use in later discussion. For Mrk 421, we show

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| Date       | Telescope | Instrument       | Filter/Grating |
|------------|-----------|------------------|----------------|
| 1997 Mar 5 | HST       | WF/PC2           | F702W          |
| 1999 Feb 19 | Palomar 5 m | Double Spectrograph | 600/300 lines mm⁻¹ |
| 1999 May 24 | HST       | WF/PC2           | F555W          |
| 1999 May 24 | HST       | WF/PC2           | F814W          |
only an estimate of the $R$ magnitude of the nucleus for comparison with Mrk 421-5; in the 1999 May observations in the F555W and F814W filters there were no exposures short enough to avoid saturation of the nucleus.

Based on the expected contributions of the different components indicated by Figure 3, the nuclear magnitude may contain a significant bulge contribution, of order 30%–40%. In spite of this, it still appears that the bright nucleus is too compact to be a typical star-forming region. As we discuss in a later section, it is likely to be either a compact nuclear star cluster or more probably an active nucleus. And although there is only a marginal difference in color between the nucleus and the annular bulge region, it does favor a rise of the nucleus relative to the bulge in the near-infrared, which is consistent with Seyfert-nucleus behavior.

The nucleus of Mrk 421 itself is highly variable in the visual bands. In fact, the $HST$ observations in early 1997 occurred shortly after a large optical outburst (Tosti et al. 1998) during which the $R$-band magnitude peaked at brighter than 12. During 1997 March Tosti et al. estimated

**TABLE 2**

| Source                  | $V$ | $R$ | $I$ | $V-R$ | $V-I$ | $M_R$ |
|-------------------------|-----|-----|-----|-------|-------|-------|
| Mrk 421 AGN             | ... | 12.74 | ... | ...   | ...   | -23.0 |
| Mrk 421-5 nucleus ($r \leq 0'18$) | 19.66 | 19.11 | 18.53 | 0.56  | 1.14  | -16.6 |
| Mrk 421-5 bulge (0'18 $\leq r \leq 1'1$) | 19.62 | 19.05 | 18.41 | 0.58  | 1.21  | -16.7 |

* Units are magnitudes, and standard errors are typically 0.04 mag. No unsaturated $V$- or $I$-band exposures of the nucleus of Mrk 421 were available.
3. OPTICAL SPECTROSCOPY

Low resolution optical spectra of Mrk 421 and its companion were obtained with the double spectrograph on the 5 m Palomar telescope during the night of 1999 February 19. The long slit (2") with a 2" aperture was centered on the companion galaxy and two 600 s exposures were obtained. The slit was positioned at an angle of 53°, and passed through both the companion galaxy and the nucleus of Mrk 421. A 5500 Å dichroic was used to split the light to the two sides (blue and red), providing nearly complete spectral coverage from 3600–7600 Å. The blue spectra were acquired with the 600 line mm$^{-1}$ diffraction grating (blazed at 4000 Å). The red spectra were acquired with the 316 line mm$^{-1}$ diffraction grating (blazed at 7500 Å). Thin 1024 x 1024 Tek CCDs, with read noises of 8.6 e$^{-}$ (blue) and 7.5 e$^{-}$ (red), were used on the two sides of the spectrograph. Both CCDs had a gain of 2. e$//$digital unit. The effective spectral resolution of the blue camera was 5.0 Å (1.72 pixel$^{-1}$); the effective spectral resolution of the red camera was 7.9 Å (2.47 pixel$^{-1}$). The spatial scale of the long slit was 0.62 pixel$^{-1}$ for the blue camera and 0.48 pixel$^{-1}$ for the red camera.

The spectra were reduced and analyzed with the IRAF package. The spectral reduction included bias subtraction, scattered light corrections, and flat fielding with both twilight and dome flats. The two-dimensional images were rectified based on arc lamp observations (Fe and Ar for the blue side; He, Ne, and Ar for the red side) and the trace of stars at different positions along the slit. The sky background was removed from the two-dimensional images by fitting a low-order polynomial along each row of the spectra. One-dimensional spectra of Mrk 421 and its companion were extracted from the rectified images using a 1.5 extraction region (the seeing disk at the time of the observations) centered on the peak emission of each system. In addition, a galaxy spectrum for Mrk 421 was obtained by averaging together two 4Å regions offset from the nucleus by ±4". While the night was nonphotometric, observations of standard stars from the list of Oke (1990) provided calibration for the fluxes, which are estimated to be accurate to about 10%. The flux-calibrated spectra are presented in Figure 4, in units of ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$. We estimate an overall uncertainty of 20% in the flux calibration due to variations in the transparency during our observations.

3.1. Spectrum of Mrk 421

As seen in Figure 4a, the nucleus of Mrk 421 is dominated by nonthermal emission with very weak absorption features. This new spectrum is similar to other observations of the nucleus of Mrk 421 (e.g., Marcha et al. 1996), with the exception that [O I], [N II], and Hα emission lines have been detected. While measurement of relative fluxes for the narrow emission features is complicated by the presence of...
broad H\textalpha{} emission (Fig. 5) and by the contamination of H\alpha{} absorption from the underlying stellar population (see Fig. 4b), the [N \textsc{ii}] lines are significantly stronger than the narrow H\alpha{} feature. Large [N \textsc{ii}]/H\alpha{} ratios are not uncommon in AGNs, however (e.g., Veilleux & Osterbrock 1987). Both the broad and narrow emission lines appear to be associated only with the nucleus of Mrk 421.

In Figure 5 we plot a fitted continuum model for Mrk 421 along with the measured spectrum in the region near the detected emission lines. Although the continuum model does not account for all of the structure in the spectrum near the emission lines, it does qualitatively indicate the intrinsic width of the broad line emission, which has a FWHM of order 80 Å, with detectable emission that extends out to nearly twice this value. The implied velocity dispersion is roughly 5000 km s\(^{-1}\). We discuss some of the implications of this in a later section.

Recently, Morganti et al. (1992) obtained narrow band images roughly centered on the H\alpha{} and [N \textsc{ii}] lines and reported a total H\alpha{} + [N \textsc{ii}] flux of \(1.6 \times 10^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\) for Mrk 421. The present observations are the first spectroscopic detection of emission lines associated with the nucleus of Mrk 421, confirming this result. The total integrated flux in the broad and narrow emission lines is \(1.7 \times 10^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\) (EW \sim 2.2 Å). We estimate an overall uncertainty in this value of about 20%.

This apparent agreement with Morganti et al. is somewhat misleading, since our estimate includes flux spread over more than 100 Å, while the Morganti et al. estimate was based on a 50 Å FWHM filter, which was apparently offset with respect to the centroid of the emission. Thus we actually have detected a significantly lower total flux level than Morganti et al., although we cannot quantify the difference without a more accurate knowledge of the filters used by Morganti et al. Despite the new detection of emission lines, Mrk 421 still falls under the general class of BL Lac objects: the 4000 Å break has a low contrast in the nuclear regions and the derived equivalent widths for the emission lines are significantly less than 5 Å.

The sudden appearance of emission features in previously featureless spectra of BL Lac-type objects is becoming quite common. Just a few years ago, such features were detected in the prototypical BL Lac, BL Lac itself, for the first time (Vermeulen et al. 1995; Corbett et al. 1996). Similar events were discovered in OJ 287 (Sitko & Junkkarinen 1985) and PKS 0521-365 (Ulrich 1981; Scarpa, Falomo, & Pian 1995) as well. The rise and decline of emission-line features in BL Lac-type objects poses an interesting puzzle and monitoring of these lines should be done as often as possible to determine if their intensity is correlated to that of other bands.

3.2. Spectrum of the Host Galaxy

A spectrum of the underlying host galaxy was obtained by averaging spectra on either side of the nucleus (Fig. 4b). As found in other spectroscopic observations of the host galaxy (e.g., Ulrich et al. 1975; Ulrich 1978), the spectrum is dominated by absorption features. In addition to the usual strong absorption features in the blue, the Na \(\text{i}\) \(\lambda\lambda 5890, 5896\) doublet is remarkably strong throughout the galaxy. We note that the presence of an apparent broad emission bump in the region of the spectrum surrounding the H\alpha{} absorption line is apparently due to scattered emission from the extremely bright active nucleus of Mrk 421.

3.3. Spectrum of Mrk 421-5

Similar to the host galaxy of Mrk 421, the spectrum of the companion galaxy is dominated by absorption lines (Fig. 4c). However, the presence of strong Balmer absorption features indicates that this system is not dominated only by an old stellar population; rather, it must have had recent star formation activity within the last gigayear or so.

The plethora of absorption lines in the optical spectrum permits an accurate redshift determination for this system: \(9380 \pm 50\) km s\(^{-1}\). Ulrich (1978) was one of the first to point out that Mrk 421 is part of a large group of galaxies;
we now know that radio galaxies tend to form in groups (Zirbel 1997). The close proximity (spatially and in velocity space) of Mrk 421 and Mrk 421-5 suggests that these two systems may have had significant tidal interactions in the past and may explain the unusual stellar population of the companion.

3.4. Spatially Resolved Na Absorption

Both Mrk 421 and its companion galaxy have high signal-to-noise Na I absorption features, which can be used to trace their gas kinematics. A position-wavelength diagram for the two systems is shown in Figure 6. The Na line can be traced almost continuously from Mrk 421 to Mrk 421-5. The mean velocity as a function of position along the slit for several of the absorption lines is shown in Figure 7. The errors in each individual measurement are largely due to the relatively low signal-to-noise ratio and the somewhat coarse spectral resolution of the observations; nonetheless, the two systems are clearly offset in velocity, with a sense of velocity continuity between the two galaxies.

Figure 7 also displays the results of unconstrained least-squares fits for the velocity gradients across each of the two systems. The results of these fits are shown in Table 3. The velocities are not corrected for earth orbital motion; however, the correction for the hour angle of our observation is negligible compared to the errors in the estimates in Table 3.

3.5. On Limits to Radio Emission from Mrk 421-5

A number of VLA studies of Mrk 421 and its immediate vicinity were conducted soon after it was recognized to be a BL Lac object (Ulvestad & Johnston 1984; Ulvestad, Johnston, & Weiler 1983); however, the resolution of these studies was not adequate to show the companion, in part because of the high dynamic range required (Mrk 421 is 0.57 Jy at 20 cm). More recent 20 cm observations (Laurent-Muehleisen et al. 1993) with higher resolution show complex extended emission in the vicinity of Mrk 421, but probably do not have enough dynamic range to detect the companion galaxy nucleus, if its brightness is comparable to the average of its class.

Although there are conspicuous examples of radio-loud Seyferts (primarily Seyfert 1) more typical Seyfert nuclei of both type 1 and 2 emit total fluxes of order $10^{21}$ W Hz$^{-1}$ at
cm wavelengths (see Ulvestad & Wilson 1989 and references therein). At the distance of the companion, this luminosity would produce about 0.5 mJy of 3.5 cm flux density, and a factor of 2–3 more than this at 20 cm for a typical Seyfert spectral index of $-0.5$ to $-0.7$. Inspection of a number of VLA maps at various resolutions shows no source of significant strength at the companion galaxy position. However, the complex halo of emission around Mrk 421 precludes identifying a source at a level below 1 mJy. Further radio observations should be made to attempt to identify any compact source associated with the companion galaxy nucleus.

4. DISCUSSION

4.1. The Nature of the Companion

The absolute magnitude of the nucleus of Mrk 421-5 was given in Table 2 as $M_R = -16.6$. If we assume this magnitude contains a 40% background contribution from the galaxy of Mrk 421-5, the nucleus still has $M_R = -16.0$ and a corresponding $M_V \approx -15.5$. It is thus apparently as bright or brighter than any of the compact nuclear clusters described from HST observations by Phillips et al. (1996) and Carollo et al. (1997) which fell mostly in the range of $M_V = -12$ to $-14$. A recent detailed HST study of four nearby spirals with compact nuclei (Matthews et al. 1999) gave $M_B$ values that range from $-8.5$ to $-10.4$ and corresponding $M_I$ values of $-9.9$ to $-11.4$.

Compact star cluster nuclei are not uncommon among late-type spiral galaxies, although they are often difficult to detect in ground-based images. However, based on the photometric results presented above, the nucleus of Mrk 421-5 must be among the most luminous in its class if it comprises an overluminous nuclear cluster.

The alternative is that we are viewing a Seyfert nucleus near the low end of the Seyfert luminosity range. In fact, recent studies have shown that the Seyfert luminosity function extends well below the luminosity of Mrk 421-5 (Ho et al. 1996, Ho et al. 1997). It is also worth noting that Malkan, Gorjian, & Tam (1998), in an HST survey targeting known or potential Seyfert galaxies, found that the presence of a bright, unresolved nucleus in HST images was a nearly perfect indicator of Seyfert activity in a survey of several hundred objects. Thus the lack of emission lines from the nucleus of the companion galaxy is puzzling, given the other indications that the source is nonthermal in nature. However, given the mediocric seeing conditions during the spectroscopic observations and the extreme compactness of the core, our constraints on emission lines are not yet very strong.

The HST results indicate that we are viewing the companion at a substantial inclination relative to its spiral axis. This could contribute to the lack of observed emission lines due to obscuration. If the galaxy is a Seyfert 2, the narrow line emission may in fact be sufficiently diluted by the galactic bulge that it will be difficult to observe from the ground. From the HST image, the nuclear source is probably unresolved; even if we assume its diameter to be 0′:1, the dilution factor under our seeing conditions (1′:2) is at least a factor of 10, after accounting for the brightness of the nucleus relative to its surrounding bulge. Clearly, interpretation of any ground-based observations of this and other similar objects must be tempered with caution because of the danger of these dilution effects.

4.2. Implications of the Velocity Measurements

4.2.1. Mass of Mrk 421 Bulge

As noted above, the shape of the velocity curve is consistent with the behavior expected from tidal interaction. This, combined with the proximity of Mrk 421-5 to Mrk 421 and the presence of a group of galaxies of similar redshift, leads to the conclusion that Mrk 421-5 is undergoing an orbital encounter with Mrk 421. Also, since Mrk 421-5 is much closer to Mrk 421 than any other galaxy in the group, we may treat the pair as a binary system for purposes of estimating the dynamical masses involved.

The statistics of binary galaxies have been treated in detail by Noerdlinger (1975) who showed that the assumption of circular orbits for a binary pair is a conservative one with regard to mass estimation. In fact, the circular orbit approximation is valid up to eccentricity of $e \approx 0.4$ and underestimates the mass by only a factor of 3 in the limit of a parabolic encounter ($e = 1$).

Thus we estimate a lower limit to Mrk 421’s mass $M$ within the companion’s present projected orbital radius $R_p$:

$$M(R_p) \geq \frac{U_r^2 R_p}{G},$$  

where $U_r$ is the companion’s radial velocity and $G$ is the gravitational constant.

For $U_r = 496$ km s$^{-1}$ and $R_p = 10$ kpc in the comoving frame, the lower limit of the mass is

$$M(R_p) \geq 5.9 \times 10^{11} M_\odot.$$

For moderate orbital eccentricity ($e \leq 0.4$), Noerdlinger (1975) has shown that the most probable values of the total velocity $U_p$ and true separation $R_p$ are likely to be 20%–30% higher than the observed values. Thus the most probable value for the bulge mass is about twice the value above, of order $10^{12} M_\odot$. Typical giant elliptical rotation curves increase out to radii of order 10 kpc, then turn over and continue flat out to 50 kpc or more. Since a flat rotation curve implies a linear increase of the dark halo mass with radius, we expect that only of order 10%–20% of the total mass of the Mrk 421 system is likely to reside within $R_p$; the total mass of the galaxy probably approaches $10^{14} M_\odot$, among the highest masses of giant elliptical galaxies. Further measurements of the virial velocities of other members of Mrk 421’s group should be able to confirm this.

4.2.2. Mass-to-Light Ratio

The CCD photometry of Mrk 421 reported by Kikuchi et al. (1987) gives the absolute $V$ magnitude of the Mrk 421 host galaxy within a 13′′ radius of $M_V(13′′) = -21.51 \pm 0.03$, implying a luminosity of $3.5 \times 10^{10} L_\odot$. Note that the emission from other bands, such as radio continuum and X-ray, is almost entirely associated with the AGN rather than the galaxy. Thus, the implied minimum mass-to-light ratio is $M/L \geq 17$, indicating a substantial dark matter contribution to the total mass of Mrk 421 within $R_p$.

This calculation ignores the possible contribution of atomic or molecular gas to the total mass, but no HI has been detected in this system (van Gorkom et al. 1989). IRAS measurements of far-infrared fluxes of Mrk 421 (Knapp et al. 1990) have been interpreted as due to the presence of a total dust mass of order $5 \times 10^7 M_\odot$. If a gas component were present corresponding to this dust level, one might expect up to $10^9 M_\odot$ of gas in the total galaxy; only a
fraction of this would be within $R_p$. Thus we expect our derived $M/L$ ratio to be robust.

A number of statistical estimates of the mass-to-light ratios of binary galaxies have yielded values with ranges of 12–32 for pure spiral pairs (Schweizer 1987; Honma 1999) and 22–60 for elliptical pairs (Schweizer 1987). These estimates use galaxies with mean separations of order 60–100 Kpc, and they thus include a much greater mass fraction of the whole galaxy than our estimate. As discussed above, typical giant elliptical rotation curves lead one to expect that the total $M/L$ for Mrk 421 may be 5–10 times higher than what is measured for this close pair.

4.2.3. Estimates of Mrk 421 Central Black Hole Mass

Wandel (2000), Wandel, Petersen, & Malkan (1999), Laor (1998), and others have noted the correlation of AGN host galaxy bulge mass $M_\text{bulge}$ to the mass of a central black hole $M_{\text{BH}}$ in cases where a reliable virial mass or reverberation mapping mass could be estimated. Wandel (2000) finds a relation of $M_{\text{BH}} \approx 3 \times 10^{-4} M_\odot$ in a sample composed primarily of low-luminosity AGNs for which the statistics are reasonably good. Magorrian et al. (1998), in a comprehensive study of kinematics of normal galaxies, found a relation $M_{\text{BH}} \approx 6 \times 10^{-3} M_\odot$. If we use these values to bound the likely value of $M_{\text{BH}}$ for Mrk 421, and assuming that our estimate of the lower limit to the mass within $R_p$ is dominated by the bulge mass of Mrk 421, we expect a central black hole mass in the range $1.8 \times 10^6 \leq M_{\text{BH}} \leq 3.6 \times 10^9 M_\odot$.

We can also use the parametric relations given by Laor (1998) and Wandel et al. (1999) to make an independent estimate of the size of the broad-line region (BLR) based on the AGN bolometric luminosity. Wandel et al. give a black hole mass estimate based on the size of the BLR and $\Delta v_\text{FWHM}$, the FWHM of the measured broad-line velocity dispersion

$$M_{\text{BH}} \approx 1.45 \times 10^5 M_\odot \left( \frac{c t_{\text{BLR}}}{1 \text{ lt-day}} \right) \left( \frac{\Delta v_\text{FWHM}}{1000 \text{ km s}^{-1}} \right)^2 .$$

The size of the BLR can be estimated from (Kaspi 1997; Wandel et al. 1999)

$$r_{\text{BLR}} = 15 L_{44}^{1/2} \text{ lt-days},$$

where $L_{44}$ is the bolometric luminosity For Mrk 421, estimates of the bolometric luminosity over the 0.1 to 1 $\mu$m band vary considerably, and it is unclear whether the quiescent or high-state luminosity is more appropriate. Using a bolometric luminosity derived from our $HST$ magnitudes and the conversion given in Laor (1998), we find $L_{44} \sim 40$, which gives $r_{\text{BLR}} \approx 90$ lt-days. Assuming that $H_\alpha$ is dominant in forming the broad line emission, then we use $\Delta v_\text{FWHM} \approx 3300 \text{ km s}^{-1}$ from our spectrum above. The implied black hole mass is then $M_{\text{BH}} \sim 1.4 \times 10^8 M_\odot$, which is of the same order of magnitude as the lower limit estimate from the bulge mass above.

A black hole mass of $10^8 M_\odot$ is of order 0.25% of the total dynamical mass out to 10 kpc. Thus it is not in itself enough to affect the large-scale dynamics between the two galaxies, although it would certainly strongly influence the inner bulge regions. It is notable, however, that the center of mass of the system will likely be significantly displaced from the position of the black hole, perhaps by a few hundred parsecs or more, depending on the companion mass and the dark matter distribution. Careful measurements of the virial motion of the stars near the center of Mrk 421 may be able to detect such an offset, which would provide independent confirmation of the proximity of Mrk 421-5 to Mrk 421.

4.2.4. The Dynamical State of the System

The smooth rise in the rotation curve of Mrk 421 out to $R_p$ is consistent with expectations for a postencounter system, in which any major velocity distortions produced by the encounter have relaxed and bulk tidal motions now dominate. However, we cannot rule out the possibility that this is the companion’s first approach toward Mrk 421. It is also possible that there are distortions in the velocity curves that are unresolved at our present sensitivity. Since we cannot unambiguously infer the companion’s true velocity from radial velocity measurements alone, we cannot prove that the system is bound, and we can only base our estimates of the tidal effects on the global properties we observe. Despite these caveats, there are a number of different lines of evidence that point to a bound and tidally relaxed system.

An obvious, though not compelling, piece of evidence is the fact that we observe the companion galaxy this close to Mrk 421 at all at the relatively late epoch of the system. The probability that we are observing a first encounter between two high-ranking cluster galaxies cannot be estimated based on this single case alone. However, based on the galaxy count of Ulrich (1978) and on our own Palomar images over a 12' field around Mrk 421, there are potentially seven to 10 galaxies of comparable brightness to Mrk 421-5, in a volume of order $6 \times 10^{16}$ pc$^3$, of order $10^4$ times the volume containing Mrk 421 and its companion. Since Mrk 421 will probably tend to significantly perturb the local potential, the chance of near encounters with it are not determined simply by chance; however, we estimate that the chance observation of such an encounter is of order 1% or less for any snapshot of similar clusters.

If the system is not in the initial phase of a first encounter, it follows that (1) it is likely to be bound (because of the mass dominance of Mrk 421 and the narrow range of phase space required for Mrk 421-5 to have the required escape velocity) and (2) that it is tidally relaxed, since the relaxation time for the system as observed is in the range of 100 Myr, relatively short compared to the time of cluster formation.

The evidence for recent star formation in the companion galaxy is also relevant to discussion of the dynamics of this pair. Recent simulations of hierarchical galaxy encounters (see Bekki 1999 and references therein) have shown that star-forming activity in the satellite galaxy is a likely result of such an interaction. A number of recent $HST$ studies have found a significant number of companions near QSO host galaxies (Bahcall et al. 1995; Disney et al. 1995) that appear to be undergoing some type of interaction with the QSO host. Canizalo & Stockton (1997) found that at least one companion galaxy in such a system (PG 1700+518) showed evidence of a relatively young stellar population.

What is perhaps surprising in the case of Mrk 421 and Mrk 421-5 is that, although simulations such as those of Bekki (1999) indicate that the companion galaxy is likely to evolve to a dwarf elliptical or irregular as a result of the encounter, Mrk 421-5 appears in fact to be a relatively normal spiral, without any apparent major disruption or irregularity. This system thus presents a challenge to models that cannot account for preservation of such structure even in what was probably a strong tidal encounter between
these two systems. It is notable that Mrk 421-5, as a probable Seyfert, is likely to have a massive compact object in its nucleus. Based on arguments similar to the previous section and our estimates of the bulge luminosity of Mrk 421-5, the expected mass is in the range of $2 - 5 \times 10^8 M_\odot$. The presence of this large central mass may in fact have important dynamical consequences in stabilizing a satellite galaxy in such an encounter.

4.2.5. A Schematic Geometry for the System

To postulate a possible three-dimensional geometry for this pair of galaxies, we combine a number of related pieces of evidence that bear on the geometry, including our measured velocity curves, the apparent inclination of the companion spiral, the major and minor axes of Mrk 421, and parameters associated with the central mass of Mrk 421, although the latter are included mainly for comparison rather than as constraints on the global geometry.

The position angle of the center of the companion relative to Mrk 421 is $53^\circ$, and we estimate that the projected major axis of the spiral lies at a position angle of $65^\circ$. Thus the projected rotation axis (perpendicular to the major axis of the spiral) of Mrk 421-5 is at a position angle of $335^\circ$. The inclination of the spiral is more difficult to estimate, since the shape may be confused by an inner bar feature not easily distinguished in the images. However, it appears that the spiral inclination is in the range of $45^\circ$ to $60^\circ$ to the line of sight.

If we assume that the disk of the spiral and the orbital plane are roughly coincident (this is reasonable if the systems are tidally relaxed), then we can make a first-order schematic estimate of the overall geometry of the system, if the two galaxies are bound in an orbit of only moderate eccentricity. This schematic view of the system is depicted graphically in Figure 8. We have not attempted to quantify this geometry further; we present it simply as a qualitative baseline, which can be refined (or revised) by future observations.

Recent VLBI imagery and estimates of the jet Doppler factors from both VLBI and gamma-ray observations (Piner et al. 1999; Gaidos et al. 1996) indicate conclusively that the jet angle must be $\leq 5^\circ$ with respect to the observation vector. The projected position angle of the inner jet from VLBI observations is about $320^\circ$. We have plotted this position angle in Figure 8 for comparison. For the case of a small angle with respect to the line of sight, the approximate coincidence of the projected position angle with that of the spiral axis and the possible orbital plane is presumably an accident. However, if the jet is actually physically aligned with the other angular momentum vectors in the system, then a much larger angle for it with respect to the line of sight is favored.

An outstanding question in Mrk 421 and in BL Lac objects in general is how well aligned the jet axis is with the line of sight to the AGN. If the results based on estimates of the Doppler factors are correct, and the jet axis is inclined by $\leq 5^\circ$, then we are led to conclude that either the orbital plane of the two galaxies is not well aligned with the perpendicular to the jet axis or plane of the spiral companion is not well aligned with the overall orbital plane. In either case the residual torques may have observable consequences, either in precession effects or tidal velocity distortions of the system. More complete velocity mapping may provide information on the latter consequence. As to the former effect, further analysis is necessary to estimate whether there might be observable effects, since the precession timescale would be expected to be long compared to the orbital timescale.

4.2.6. Companion Rotation: Prograde or Retrograde?

We conclude this section by briefly noting the sense of the companion rotation. The rotation curve shown in Figure 7 shows that the eastern end of Mrk 421-5 is redshifted relative to the western end, which is closest to Mrk 421. This indicates a rotation that is clockwise on the sky, and it corresponds to a prograde rotation relative to the projected rotation of the bulge of Mrk 421.

This feature of the system may be important to the stability of the companion. Future simulations should look in more detail at the effects of retrograde versus prograde rotation in a tidal encounter.

5. CONCLUSIONS

We have gathered evidence that supports the following conclusions:

1. Mrk 421's nearest companion galaxy Mrk 421-5 appears to be an early-type spiral, rather than elliptical. Spectral evidence suggests moderately recent star formation activity in the companion, a feature that is known to accompany galaxy interactions.

2. Mrk 421-5 contains a Seyfert-like nucleus, but it is without detectable emission lines in ground-based spectroscopy. We find that its luminosity is probably too high for a compact nuclear star cluster and conclude that it is most likely to be an AGN, in spite of the lack of spectroscopic evidence.

3. We confirm the published radial velocity for Mrk 421-5. We find that Mrk 421-5 is very likely to be bound to Mrk 421, and its orbital velocity is consistent with the trend in the bulk rotational velocity of Mrk 421, suggesting tidal interaction.

4. We report the first spectroscopic observation of emission lines from Mrk 421's nucleus, notably H z and N ii. Both broad and narrow components of H z are present, with the broad line emission showing a velocity dispersion of several thousand km s$^{-1}$, typical of QSO emission lines. Spectroscopic monitoring of these lines should continue.

![Diagram of Mrk 421 and Mrk 421-5 system](image-url)
5. The observed orbital velocity of the companion Mrk 421-5 provides a lower limit on the mass of Mrk 421’s bulge of $5.9 \times 10^{11}$ solar masses, with an estimated bulge mass-to-light ratio of $\gtrsim 17$.

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