Reports

Markarian 348: A Tidally Disturbed Seyfert Galaxy

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Combined optical and radio images of galaxies can provide new insights into the sizes, masses, and possible evolution of these objects. Deep optical and neutral hydrogen images of Markarian 348, a type 2 Seyfert galaxy, show that it is a gigantic spiral (perhaps the largest known non-cluster galaxy). Measurements of the neutral hydrogen velocity field and spiral structure, and detection of an optical "tidal plume," all provide evidence that it has been subject to tidal disruption. The measured velocities yield a mass-to-light ratio for this object (within a radius of 130 kiloparsecs from its nucleus) that is similar to the ratio found for the inner regions of most galaxies of similar type. This is one of the few cases where detailed velocity measurements have demonstrated that a galaxy with an active nucleus has been subject to extensive tidal perturbation.

MERGERS, PERTURBATIONS, AND tidal interactions between galaxies have become popular topics in astronomy. Such gravitational effects have been credited with both fostering nuclear activity in galaxies and driving the course of galaxy evolution (*1*), yet there is very little direct observational evidence for either of these effects. Most of the evidence is circumstantial, consisting of (i) theoretical calculations and general arguments, which show that under proper conditions gravitational perturbations can push mass toward the centers of galaxies (*2, 3*); (ii) morphological similarities between some Seyfert galaxies and radio galaxies, and morphological features predicted by crude theoretical models that describe galaxies disturbed by tidal encounters or mergers (*1, 3, 4*); and (iii) statistical correlations between an excess of projected galaxy companions and the incidence of abnormal activity (*1, 5, 6*). Direct evidence of tidal interaction should include not only the proven proximity of a companion and the identification of morphologically peculiar features, but also a demonstration that the object's detailed velocity field is consistent with that predicted for such an encounter.

To understand the relation between external gravitational disturbances and enhanced nuclear activity in galaxies, we must study proven examples of the phenomenon in detail. Quantitative analysis of the luminosity structure and detailed internal mass flow of these objects, coupled with detailed computer models that simulate these properties under various gravitational perturbations, can then provide information about the types of disturbances that will lead to nuclear activity. To date, there are very few proven cases of active galaxies in interaction that can serve as subjects for such studies (*7*). In this report we present detailed data on one object [Markarian (Mkn) 348, also known as NGC 262], which provide clear evidence for a large-scale tidal disturbance in this active galaxy. Our data demonstrate all of the criteria noted above: morphological peculiarities, a close companion, and an internal velocity field that is consistent with the velocity field predicted for such an encounter.

This study of Mkn 348 is part of a larger program to obtain deep surface photometry and large-scale velocity fields for a sample of nearby Seyfert galaxies that show morphological peculiarities indicative of gravitational perturbation (*3*). The galaxy itself is a "type 2" Seyfert galaxy with an unresolved radio continuum core (*8*), which is known to have a large halo of neutral hydrogen (H I) with peculiar kinematics (*9–11*). We will assume a distance for this object of 95 megaparsecs (Mpc), based on a Hubble constant, H_0, of 50 km sec^{-1} Mpc^{-1} (*12*).

The optical data presented here were obtained from four deep Palomar Schmidt images (90-minute exposures) taken with broadband filters centered at approximately 4800 Å and 6500 Å (called g and r, respectively) (*13*). These were calibrated with charge-coupled detector (CCD) measurements. The radio data are from Very Large Array (VLA) radio telescope observations of the H I 21-cm emission line (*14*). The final images are shown in Figs. 1 to 3 and on the cover. The total H I emission is shown in Fig. 1, A and B. The size of the H I spiral in Fig. 1 is at least $11.7' \times 14.9'$ (roughly 310×395 kpc, scaled as $H_0/50$), whereas earlier observations detected H I over an area of $9.5' \times 8.3'$ (*9*). Thus, we have almost doubled the size of the image of this object in its east-west extension, and we now believe that this is the largest known non-cluster galaxy (*15, 16*). This increase in size was obtained by increasing the sensitivity of the observations by only a factor of 3. A further increase in sensitivity might reveal even more H I. The extensive distribution of spacings provided by the VLA in its most compact configuration makes this array an ideal instrument for the detection of large-scale, smooth distributions of H I.

An underexposed print of the H I image is shown in Fig. 1B. Earlier H I observations suggested that the outlying gas in this galaxy was distributed in a ring (*9*). Although the H I distribution in Fig. 1, A and B, is superficially ringlike, the present observations show that the gas actually lies in one (or possibly two) continuous, branching spiral arms which are more tightly wound near the center.

The image in Fig. 1C is the sum of the optical images processed to remove all of the foreground starlight and smoothed to the same resolution as the H I image (*17*). The brighter stars in the field have been superimposed on the processed image to provide a reference frame. The outer arm (marked by the arrows in Fig. 1C) is coincident with the fainter (top) H I arc emerging from the same point (see Fig. 4 for a clarification of the two H I arcs in this region). The light from this optical arm has an energy distribution (indicated by the difference in magnitude between its g- and r-band intensities) similar to that of the inner parts of the optical disk (with a g to r color index of 0.5 ± 0.2 mag) (*18*) and a surface brightness in the g band ranging from 25.8 to 26.0 mag arcsec^{-2}. On the unsmoothed, deep images the arm appears as multiple, parallel, threadlike features. This type of stellar arm or "plume" is thought to be characteristic of galaxies subjected to strong tidal distortion (*1*).

The entire galaxy appears to sit on a faint optical "pedestal" with an average g-band surface brightness of approximately 26.5 mag arcsec^{-2}. This shows up in Fig. 1C as residual, patchy luminosity surrounding the central image. This faint pedestal extends to a radius of 290″ from the nucleus and then disappears in the region where the H I

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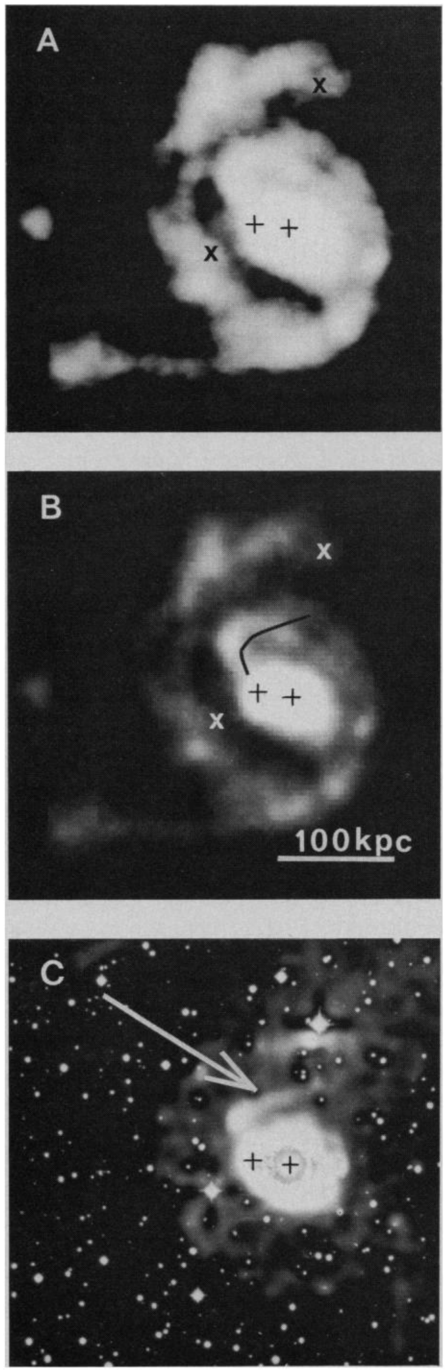

Fig. 1. (**A**) Total H I image of Mkn 348: (+) the galaxy center and its eastern companion; (**X**) two bright stars. (**B**) A lighter exposure to show the continuity of the arms. The black line on the north arm is the position of the optical "plume." (**C**) Deep optical image of Mkn 348 (with stars removed) smoothed to the resolution of the H I image (50″). Brighter stars have been superimposed on the processed image. The arrow points to the optical plume depicted by the black line in (B). 100 kpc scale bar = 3.6′.

emission drops off. The dark cross patterns and bubblelike structures that appear in the pedestal arise from a slight oversubtraction of the stars. Their appearance is artificially enhanced in this reproduction because of the need to stretch the intensity scale to display the optical plume noted above.

The cover shows a composite of the total H I (blue) and the unprocessed optical field (red), and gives a clearer picture of the inner optical regions.

The H I data for different heliocentric velocities are displayed in Fig. 2 as isointensity contours. Figure 3 shows these data summarized in a color plot of the total intensity-weighted H I velocity field. The bulk motions of the inner and outer H I regions exhibit opposing rotation patterns. (For example, in Fig. 2 there are clumps of gas at 4582 km sec^{-1} at position angles of approximately 30° and 190°, on opposite sides of the nucleus, while the clumps of gas that are mirror images of these clouds are at velocities of 4508 km sec^{-1} in position angles of approximately 220° and 10°, respectively.)

The opposing rotation patterns shown in Fig. 3 are similar to those found in the H I region surrounding NGC 5194/95 (M51, the Whirlpool Nebula) (*19*). The overall similarities between the M51 system and Mkn 348 are remarkable. (i) The optical morphology of both systems is similar [see, for example, the large-scale optical image of Mkn 348 in (*20*)]. The optical spiral structure in Mkn 348 shows less contrast with the underlying disk than that in M51. However, the disk colors for the former system are consistent with a burst of star formation approximately 2.5×10^7 to 5×10^7 years earlier than the burst that so vividly outlines the optical spiral arms in M51 (*21, 22*). This age difference is sufficient to account for the weak appearance of the spiral arms in Mkn 348, where the brightest young stars have already died out. (ii) The standard optical diameters (D_{25}) are remarkably similar for the two systems [39.9 kpc for Mkn 348 (*22*) and 36 ± 6 kpc for M51 (*22*), depending on its assumed distance]. (iii) Both objects have a satellite galaxy of comparable luminosity located at the end of their outermost spiral arm. Mkn 348 has a companion located 1.2′ to the east of its nucleus (see the cover), which has an optical spectrum with narrow emission lines whose velocity agrees with the nuclear redshift of the larger galaxy to within the measurement error of 50 km sec^{-1} (*6*). Our optical photometry in the g band shows that, within 27″ apertures, the luminosity of Mkn 348 is roughly twice that of its companion to the east. NGC 5195, the companion of M51, has a luminosity that is roughly one quarter of that of M51 in a similar spectral band and physical radius (*23*). The Mkn 348 companion is bluer than its main galaxy, whereas NGC 5194 is redder than M51; adjusting for the greater absolute luminosity expected from a bluer stellar system, we find that the relative masses of the luminous stellar material in both systems are similar.

A recent computer model by Appleton, Foster, and Davies (*19*), which successfully describes the peculiarities of the M51 velocity system, shows that the outer H I spiral structure and reversal of the H I velocity field can be caused by the passage of a satellite galaxy (such as the eastern companion of Mkn 348) through an extended H I disk of a larger galaxy. This model demonstrates that the apparent opposing rotation velocities arise because the tidal arms are warped into different planes, thus changing the projection angle of the H I orbital velocities. The model of Appleton *et al.* reproduces well the present data when scaled to the dimensions and velocities of Mkn 348. In addition, the model reproduces the projected position of the optical companion at the end of the outermost optical arm in both the M51 system and Mkn 348. This comparison implies that H I velocities and spiral pattern seen in Mkn 348 arise from the disruption of its H I disk by its eastern companion.

Although there are other galaxies besides this eastern companion located in the same field as Mkn 348, their relative faintness and lack of any connection to the structure in Mkn 348 make them unlikely candidates for interaction. For completeness, we note that there is some suggestion in the H I data that the southeastern extension and the isolated patch of H I directly to the east of the nucleus are connected (Fig. 1A). If this is the case, then the configuration of the outer spiral pattern follows the dotted extension shown in the sketch in Fig. 4. The outermost arm would then point directly towards NGC 266, a neutral hydrogen–deficient, barred spiral galaxy with a similar redshift (4670 km sec^{-1} heliocentric) located 23′ (a projected 635 kpc) to the north-northeast (*9*) (Fig. 4). Since this projected distance is only 60 percent farther than the largest dimension of the H I field in Mkn 348 itself, this configuration might suggest that NGC 266 is also connected to Mkn 348, a suggestion that has been made previously (*9*). However, the good correspondence between both the H I velocity field and the projected position of the eastern companion with the model of Appleton *et al.* strongly implies that it is this latter object that is disturbing Mkn 348.

Our data yield interesting global properties for this galaxy. Summing all of the line-emission fluxes at frequencies where we observe H I gives a total 21-cm flux of 21.5 ± 0.2 Jy, which implies a total H I mass of $4.8 \times 10^{10} M_{\odot}(50/H_0)^2$, where $M_{\odot}$ is the solar mass, if the gas is optically thin

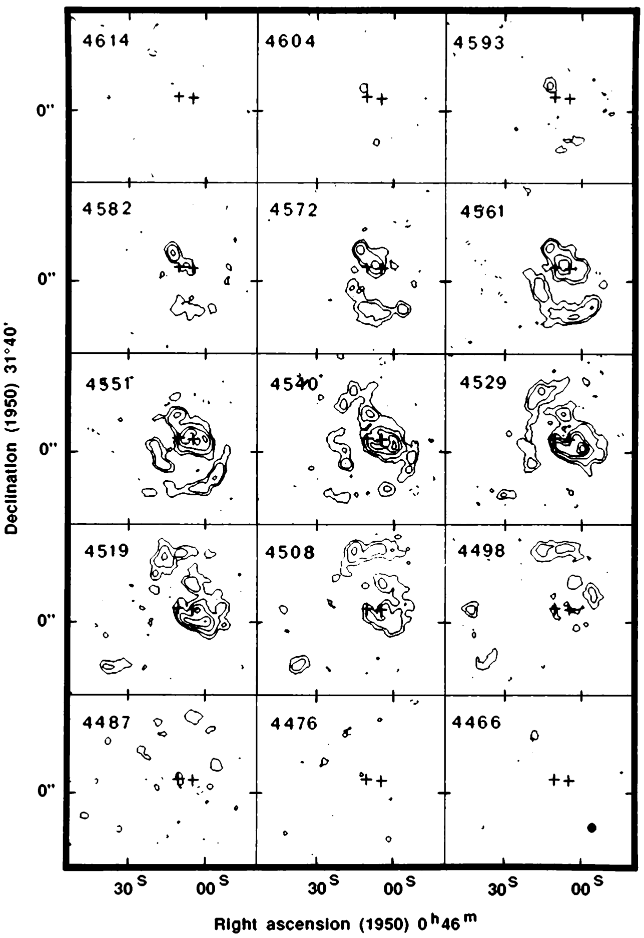

Fig. 2. Iso-intensity contours of H I at different velocities (indicated in the upper left of each frame). The filled circle in the lower right frame is the resolution; crosses mark the nucleus of Mkn 348 and its companion. Contours are −2, 2, 4, 8, 12, 16, and 20 mJy per beam. Each velocity frame is 14.5′ on a side.

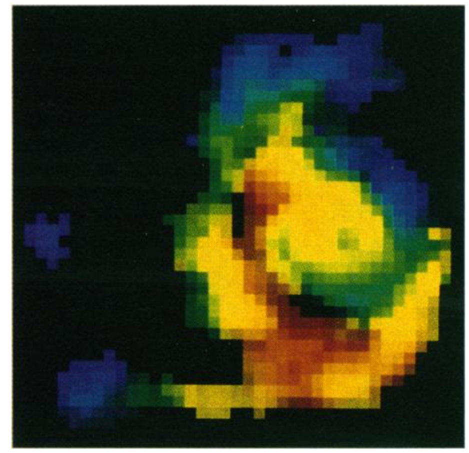

Fig. 3. Composite velocity field from the 21-cm emission line Doppler shifts. Colors range from deep red indicating a mean velocity of 4580 km sec^{-1} through yellow and green, to deep blue indicating 4490 km sec^{-1}.

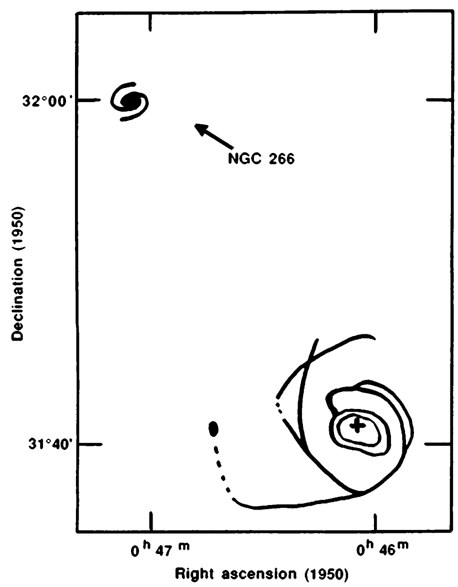

Fig. 4. Sketch of the relation between Mkn 348 and NGC 266. The arms shown for Mkn 348 are the peak of the H I intensity. Those for NGC 266 are optical.

(*24*). It is customary to use velocity data such as these to calculate the total galaxy mass. Since the model of Appleton *et al.* seems to reproduce the data well, it may be reasonable to use it as a guide for this calculation. There are gas clouds moving at a radial distance of 295″ or 130 kpc from the nucleus in the north and south regions of the outer arms (frames labeled 4487 and 4593 km sec^{-1} in Fig. 2). Both the observed continuity of the H I arms and the model itself suggest that they are still bound to Mkn 348. However, they may be in elliptical orbits with eccentricities as great as 0.6 to 0.7. In addition, the model suggests that the local concentration of clouds which makes up the arms is close enough to a ringlike structure to allow an estimate of the local inclination of the warped outer plane from the shape of the outer H I arms in these regions. The extreme possibilities are that the gas clouds are either at perigalacticon or apogalacticon. Thus, the total mass interior to this radial distance will be $1.03 \times 10^{11}\ \lambda M_{\odot}(H_0/50)(\sin i)^{-2}$, where i is the inclination angle of the plane of the orbiting gas to the plane of the sky, λ is equal to $(1 + e)^{-1}$, if the clouds are at apogalacticon, and $(1 - e)^{-1}$, if at perigalacticon, and e is the orbital eccentricity. The shape of the outer arm segments in Fig. 1B yields a value for i between 31° and 61°. Thus, the most extreme values (i = 31° and e = 0.7 at apogalacticon) give an upper limit for the total mass interior to this radius of $6.7 \times 10^{11}\ M_{\odot}$. (These values of i and e give an orbital period at this distance of $0.12/H_0$, that is, 2.4×10^9 years.) Our optical data show that the faint optical emission pedestal drops off at approximately the same radial distance as these outer H I clouds. Integrating all of the light in the cleaned optical image out to 290″ radius gives a g-band magnitude of 12.07 [or a blue magnitude (B) of 12.87 ± 0.2], which exceeds the "total" B value of 14.1 obtained by Huchra (*25*) by a factor of 3 and represents the excess luminosity observed in the deep images. This leads to a total luminosity of the material inside a 130-kpc radius of $9.7 \times 10^{10}\ (H_0/50)^2$ (in solar units). Correcting for the fraction of this material that we know to be neutral hydrogen, we obtain an upper limit to the blue mass-to-light ratio (*M*/*L*) for the nongaseous material of 6× $(50/H_0)$ (in solar units). This is similar to the value found for the inner regions of S_0 and Sa galaxies (*26*). This represents the only known example where the total mass, and thus the total mass-to-light ratio, has been measured directly for a galaxy out to this distance. All other measurements of *M*/*L* in the outer regions of galaxies rely on statistical analyses of pairs or groups of galaxies where the assumptions involved in the analysis are at least as tenuous as those involved in the present calculation (*26*). It is important to note that the present mass-to-light ratio of 6 is lower than those found by statistical methods by a factor of 8 to 20 (*26*).

The data presented here show that Mkn 348 and its eastern companion satisfy all three criteria for a tidally disturbed system. First, the optical "plume" seen in Fig. 1C is similar to those seen in simulations of interacting galaxies. Second, the eastern companion not only has a redshift similar to that of

Mkn 348, but its location at the end of the outermost, bright optical arm fits the configuration predicted by the computer model of Appleton *et al.* Finally, the continuous H I arms displayed in Fig. 1B and the observed reversals in the H I velocities are also consistent with this computer model. In combination, these observations provide strong evidence that Mkn 348 has been subjected to tidal perturbations and should therefore be a good candidate for further study of how such perturbations influence its active galactic nucleus. Additional H I measurements are needed to establish the link between NGC 266 and NGC 262, if any. Because Mkn 348 presents a unique opportunity to study the mass in the far outer regions of a galaxy by means of assumptions very different from those involved in the statistical studies of galaxy groups and pairs, it is also essential that these observations be followed by more detailed computer models of this system.

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Mutants of Bovine Pancreatic Trypsin Inhibitor Lacking Cysteines 14 and 38 Can Fold Properly

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It is a generally accepted principle of biology that a protein's primary sequence is the main determinant of its tertiary structure. However, the mechanism by which a protein proceeds from an unfolded, disordered state to a folded, relatively well-ordered, native conformation is obscure. Studies have been initiated to examine the "genetics" of protein folding, with mutants of bovine pancreatic trypsin inhibitor (BPTI) being used to explore the nature of the specific intramolecular interactions that direct this process. Previous work with BPTI chemically modified at cysteines 14 and 38 indicated that transient disulfide bond formation by these residues contributed to efficient folding at 25°C. In the present work, mutants of BPTI in which these cysteines were replaced by alanines or threonines were made and the mutant proteins were produced by a heterologous *Escherichia coli* expression system. At 25°C in vitro, the refolding behavior of these mutants was characterized by a pronounced lag. However, when expressed at 37°C in *E. coli*, or when refolded at 37° or 52°C in vitro, the mutant proteins folded readily into the native conformation, albeit at a rate somewhat slower than that exhibited by wild-type BPTI. These results indicate that, at physiological temperatures, BPTI lacking cysteines 14 and 38 can refold quantitatively.

BOVINE PANCREATIC TRYPSIN INHIBITOR (BPTI) is a 58–amino acid basic polypeptide that has three disulfide bonds: Cys14/Cys38, Cys30/Cys51, and Cys5/Cys55. When it is refolded from the fully reduced form in vitro, it proceeds to its native form via a series of preferred one- and two-disulfide intermediates (*1, 2*). Cysteines 14 and 38, which form a disulfide bond in the native molecule, participate in disulfide bonding in the most abundant two-disulfide intermediates (*1, 3*). Two of these two-disulfide bond intermediates contain non-native disulfide bonds, Cys14/Cys5 or Cys38/Cys5, in addition to the disulfide Cys30/Cys51. Creighton (*1*) showed that when cysteines 14 and 38 were blocked by reduction and alkylation, the modified BPTI could not readily regain its native conformation when refolded in vitro at 25°C. These results suggested that non-native disulfide bonds involving cysteines 14 and 38 were components of a highly preferred pathway for BPTI refolding (*1, 3*).

The above studies were open to the objection that the bulky alkylating agents used to block cysteines 14 and 38 sterically interfered with refolding. We therefore decided to repeat this experiment with genetically modified BPTIs in which cysteines 14 and 38 were replaced by alanines or threonines. The mutant BPTI proteins were synthesized by means of a heterologous expression and secretion system in *Escherichia coli* that produces native, correctly folded BPTI (*4*).

The [Ala14,Ala38]BPTI and [Thr14, Thr38]BPTI mutants were expressed by *E.*

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