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THE NATURE OF THE EXTENDED H I GAS AROUND NGC 4449: THE DR. JEKYLL/MR. HYDE OF IRREGULAR GALAXIES

Deidre A. Hunter
Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001; dah@lowell.edu
Eric M. Wilcots
Washburn Observatory, University of Wisconsin, 475 North Charter Street, Madison, WI 53706; ewilcots@uwast.astro.wisc.edu
Hugo van Woerden
Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands; hugo@astro.rug.nl
J. S. Gallagher
Washburn Observatory, University of Wisconsin, 475 North Charter Street, Madison, WI 53706; jsg@astro.wisc.edu
and
Sven Kohle
Radioastronomisches Institut der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany; skohle@astro.uni-bonn.de
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ABSTRACT

We present interferometric H I 21 cm line observations of the extended gas around the irregular galaxy NGC 4449 covering 67′ on the sky at a resolution of ∼1′. The main star-forming body of NGC 4449 is relatively normal for a Magellanic irregular galaxy, but the galaxy is unusual in that it has two counterrotating gas systems and H I that extends to 6 times the Holmberg radius. Our new, detailed H I maps of this extended gas show that most of the extended H I is located in large, highly structured, extended clouds and very long streamers. We compare NGC 4449 with other systems in the context of possible models for the origin of these structures, the most likely of which involves an interaction with another galaxy. Thus, NGC 4449 no longer fits the standard picture of an irregular galaxy quietly evolving in isolation.

Subject headings: galaxies: individual (NGC 4449) — galaxies: irregular — galaxies: ISM — galaxies: kinematics and dynamics

1. INTRODUCTION

Optically, NGC 4449 had seemed to be a fairly normal irregular galaxy. Although it lies at the more luminous and actively star-forming end of the distribution of ordinary irregular galaxies, NGC 4449 was not known to be otherwise outstanding and has often been taken as representative of the more actively star-forming irregulars. With an integrated $M_{B,0}$ of −18.4 (de Vaucouleurs et al. 1991) and a star formation rate of 0.01 $M_\odot$ yr^{-1} kpc^{-2} ($D = 3.9$ Mpc for $V_{\rm GSR} = 255$ km s^{-1} [de Vaucouleurs et al. 1991] and $H_0 = 65$ km s^{-1} Mpc^{-1}), NGC 4449 is twice as luminous as and is forming stars at twice the rate of the Large Magellanic Cloud. However, NGC 4449 is more extreme than the typical irregular galaxy in that it has neutral hydrogen gas extending to 6 times its Holmberg radius at 10^{19} atoms cm^{-2} (van Woerden, Bosma, & Mebold 1975; Bajaja, Huchtmeier, & Klein 1994), a distribution that is about 3 times more extended than most other irregular galaxies (Huchtmeier, Seiradakis, & Materne 1981).

Van Woerden et al. (1975) first mapped the large-scale H I distribution around NGC 4449 using the single-dish 100 m Effelsberg telescope, where the beamwidth is 9′. They found an elongated, symmetric distribution covering 1° × 0°.7 on the sky. Bajaja et al. (1994) reobserved the galaxy at Effelsberg and determined that the outer gas distribution has an S shape, which they interpreted as the signature of a warp. Both groups found opposite velocity gradients between the central and outer gas.

Here we present the results of radio interferometric observations of the full extent of the H I gas around NGC 4449 at a spatial resolution that is 9 times higher than had been previously used. This higher resolution resolves the extended H I gas into enormous filamentary structures and clouds. The title of this Letter is derived from the fact that NGC 4449's peculiar extended gas distribution was not predicted from the appearance of the optical galaxy or from the H I maps of the central gas.

2. OBSERVATIONS

We observed NGC 4449 at 21 cm with the Very Large Array (VLA)[1] radio interferometer in its D-array configuration in 1995 April. The telescope was stepped at half the primary beamwidth, 15′, in a 3 × 3 pointing mosaic, for a total field of view (half-power beamwidth) of 1°. The nearby galaxy DDO 125 was also observed in a separate pointing. The integration time per pointing was 40 minutes. The data were on-line Hanning smoothed. The synthesized beamwidth was 62″ × 54″, and the channel separation was 5.2 km s^{-1}, with a central heliocentric velocity of 206 km s^{-1}. The rms in one channel for the mosaicked map is 1.3 mJy beam^{-1}.

To produce flux-weighted moment maps, we smoothed the data to twice the original beamwidth and used the smoothed map as a conditional transfer at the 3.5 σ level. The resulting unsmoothed data cube was used to determine moment maps. In addition, the noisy region around the edges was removed interactively. The integrated H I map is shown in Figures 1 (Plate L5) and 2, and the velocity field is shown in Figure 3 (Plate L6).

We compared the D-array mosaic maps with the single-dish map obtained with the Effelsberg 100 m telescope (Bajaja et al. 1994) to determine the amount of diffuse emission not de-

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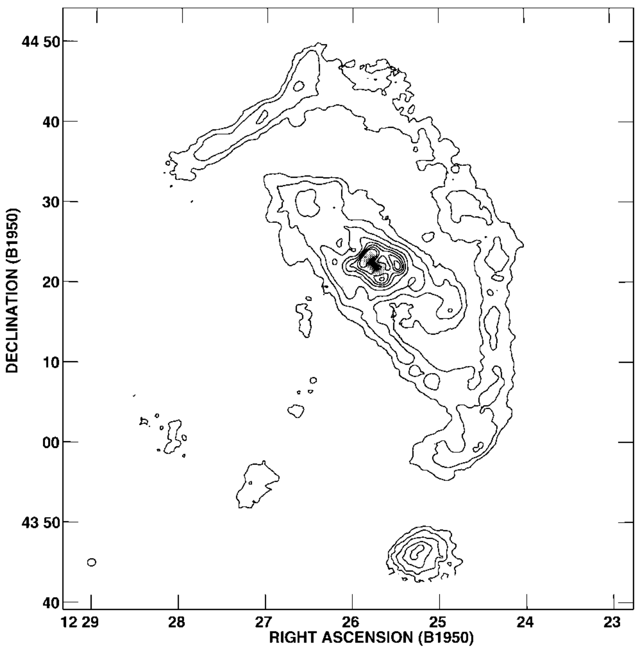

FIG. 2.—Contour map of the integrated H I distribution superposed on a gray-scale optical image of the galaxy. The contour levels are 0.7, 1.7, 3.4, 6.8, 10.2, 13.6, 17.0, and 20.4 × 10^{20} cm^{-2}. The FWHM of the beam is shown in the bottom left-hand corner of the plot. The optical image was obtained through a filter centered at 6440 Å with an FWHM of 95 Å.

tected in the D-array mosaic. To do this, we smoothed the VLA map to the same resolution (~9′) as that of the Effelsberg data, geometrically aligned the moment zero maps, converted units, and subtracted the VLA map from the Effelsberg map. Diffuse emission not detected in the VLA data is apparent.

3. RESULTS

In Figure 1, one can see a bright condensation of gas centered on the optical galaxy with a diameter of 8′ (~9 kpc). This in turn is embedded in an elongated ellipse of lower column density gas with a major axis of 35 kpc and a total H I mass of ~1.1 × 10^9 $M_\odot$. At the northeastern end of the ellipse is a concentration of gas with a peak column density of 6 × 10^{20} cm^{-2}, and at the southwestern end is a concentration with a peak column density of about half that.

Beyond the ellipse of gas is a complex distribution of clouds and streamers. A long streamer of gas emanates from the eastern side of the ellipse, extends southwest 25 kpc to a large H I concentration, curves abruptly north for about 60 kpc, and then curves to the southeast for another 26 kpc, wrapping $\frac{3}{4}$ of the way around the galaxy in the process. Another weaker streamer emanates from the northern part of the central H I condensation and extends south and then southeast about 35 kpc. There is additional weak emission to the east and to the west of this streamer. For comparison, the Holmberg diameter for this galaxy is about 10′ (11 kpc). The remarkable features of these streamers are their straight segments and abrupt angles.

The streamers, which have typical widths of 4 kpc at 7 × 10^{19} cm^{-2}, contain numerous concentrations of gas that reach peak column densities as high as 4 × 10^{20} cm^{-2}. The mass of H I in the southwestern concentration is 1 × 10^8 $M_\odot$, while the entire system of streamers, including the southwestern concentration, contains about 9 × 10^8 $M_\odot$.

Underlying the streamers is a diffuse distribution of atomic gas that is seen in the difference between the Effelsberg and VLA integrated H I maps. The VLA map appears to be missing 24% of the H I that was detected in the Effelsberg data. From a comparison of the VLA mosaic with the Effelsberg data cube, it is apparent that the missing gas is smoothly distributed over the extent of NGC 4449, with a little falling in regions where the VLA data have poor sensitivity. This missing gas implies that the mass of diffuse H I is equal to about two-thirds of the H I mass in the extended structures. The global value of $M_{\rm H\,I}/L_B$ for NGC 4449, however, falls toward the low end of the distribution for normal irregular galaxies. Thus, the extended gas is not necessarily "extra."

The gas in the central 4 kpc diameter, which corresponds to the brighter part of the optical galaxy, is seen to exhibit rotation in the opposite direction to that of the ellipse and streamers, confirming the counterrotation found by van Woerden et al. (1975) and Bajaja et al. (1994). From higher resolution VLA data (single-pointing B, C, plus D arrays), one can see that the velocity of rotation of this inner gas is about 18 km s^{-1} (Hunter, van Woerden, & Gallagher 1998); this value agrees with the result of A. Bosma & H. van Woerden (1975, unpublished). The velocities of the inner gas and the outer gas subsystems appear to be partly continuous in velocity.

In contrast to their disturbed morphology, the streamers are, at first glance, dynamically regular. In Figure 3, one can see that the streamers mimic and extend the velocities of the central H I ellipse, although with a different position angle (P.A.). However, in spite of the regularity apparent in Figure 3, neither the central ellipse beyond the counterrotating core nor the streamers fits easily into the normal rotation pattern of a disk. We fitted Brandt curves and tilted ring models to the velocity field, exploring the stability of the models, and the range in solutions is reflected in the uncertainties. For the H I ellipse located along the major axis between 2′ and 13′ radius, we find a P.A. of 230° ± 17°, an inclination of 60° ± 5°, a systemic velocity of 214 ± 6 km s^{-1}, and a maximum inclination-corrected rotation speed of 75 ± 8 km s^{-1}. Beyond 13′ radius, the streamers appear to have a P.A. of 195° ± 10°, an inclination of 50° ± 10°, a systemic velocity of 200 ± 10 km s^{-1}, and a maximum inclination-corrected rotation speed of 110 ± 10 km s^{-1}. If the outer gas really is in an approximately circular orbit, it must have been in place for at least one orbital period, which is ~2.5 Gyr at that radius and rotation speed. This would suggest that the streamers around NGC 4449 are relatively old.

The velocity profiles of the long, straight segments of the streamers, like those of most of the gas ellipse, are fairly simple with single-peak emission profiles. The velocity dispersion is of order 10 km s^{-1} (FWHM ~ 23 km s^{-1}). For comparison, the FWHM of the M81–NGC 3077 H I bridge is less than 40 km s^{-1} (van der Hulst 1979), while that of the Magellanic Stream is 25–40 km s^{-1} (Mathewson, Schwarz, & Murray 1977). The timescale for expansion of the streamers due to the velocity dispersion is of order 200 Myr, a small fraction of the rotation period. If the streamers are self-gravitating, they could maintain their morphology for longer, but we estimate that densities of order 10^{21} cm^{-2} would be required, and this is an order of magnitude higher than what is seen in the streamers. Although the straight portions of the streamers have simple profiles and a fairly low velocity dispersion, the concentrations of gas where they join and change directions have more complex profiles. In the joint in the northwest and in the southwest concentration of gas, the profiles frequently exhibit double peaks or single peaks that are broad or asymmetrical. Separations between velocity peaks of 70 km s^{-1} are seen there.

4. ORIGIN OF THE EXTENDED GAS STRUCTURES AND COMPARISON WITH OTHER SYSTEMS

In discussing the extended gas around NGC 4449, the key observational features to explain are the large streamers with their straight lines and abrupt angular turns, the counterrotation between the inner gas and the outer ellipse, and the kinematics of the streamers with respect to the central ellipse of gas. There are two basic categories of models that we will consider: continuing galaxy formation and external perturbations.

In the context of continuing galaxy formation, the streamers would represent the ongoing assimilation of primordial inhomogeneities in the extended gas around NGC 4449. That galaxy formation has lingered into the present era has been suggested, and the fact that there is considerable diffuse gas underlying the streamers lends support to this scenario. One mechanism for delaying the assimilation of extended gas was proposed by Silk, Wyse, & Shields (1987). In their model, star formation that occurs when the galaxy first forms heats the gas, which then becomes too diffuse to cool. Only later, when that gas is "bumped" by another galaxy, is the gas compressed and able to cool, and infall results. Furthermore, if the infalling gas has a different angular momentum vector, a counterrotating core can result (Quinn & Binney 1992). The superposition of an interaction scenario onto continuing assimilation addresses several difficulties with the pure assimilation scenario, including the complexity and straightness of the streamers and the short time needed for the streamers to diffuse. In this mixed scenario, the streamers are more recent structures that formed when a passing galaxy interacted with the extended, primordial gas.

Similar problems arose in early attempts to explain the origin of the Magellanic Stream. Mathewson & Schwarz (1976), for example, argued that the Magellanic Stream was of primordial origin rather than tidal because tidal models could not reproduce the observed velocities at the end of the Stream. However, when Fujimoto & Sofue (1977) tried to model an initially spherical distribution acted on by the drag force of intergalactic gas, they could not reproduce the linear morphology of the Stream. Since then, *N*-body simulations have successfully reproduced the features of the Stream as a tidal plume caused by the three-body interaction about 1.5 Gyr ago (Gardiner & Noguchi 1996).

That the streamers in NGC 4449 have resulted from an external perturbation, with or without ongoing assimilation of the original gas disk, therefore, seems likely. There are many possible interaction scenarios. A perturber could pass by, with or without giving up mass to the NGC 4449 system, and set up tidal tails and bridges; a perturber could pass through the disk, most likely off-center, setting up an expanding spiral density wave; or a satellite could have merged with NGC 4449. In addition, multiple events with more than one perturber must be considered. In some scenarios, the effects of the encounter could remain for timescales on the order of 1 Gyr, allowing the perturber to move out of the neighborhood and recover from anomalies it may have experienced or to have been digested by NGC 4449.

The interaction scenario especially draws strength from the remarkable similarity in morphology of the streamers to those seen in the M81/NGC 3077/M82 system (van der Hulst 1979; Yun, Ho, & Lo 1994). In that system, M81 plays the part of NGC 4449, and the morphology of the gas, minus that around M82, can be matched with that around NGC 4449 to remarkable detail. The M81 system has been modeled by Yun (1992) and Thomasson & Donner (1993), and a good fit is found with a model in which NGC 3077 moves in a parabolic prograde orbit in the plane of the M81 disk and part of the streamers is material that has been pulled from NGC 3077. The timescale for this interaction is modeled to be 3×10^8 yr.

There are, however, differences between the M81 system and NGC 4449. First, M81 does not have a central counterrotating gas system. This suggests that something different, or at least something additional, has happened to NGC 4449. Second, in the case of NGC 4449, we have only one obvious component of the three-body interaction. In the analogous location occupied by NGC 3077 in the M81 system, we find the southwestern concentration of gas in the streamers of NGC 4449. The mass of H I gas in that concentration is about 11% of the H I mass of the NGC 4449 system excluding the streamers; the mass ratio of NGC 3077 to M81 is similar, at 15% (Thomasson & Donner 1993). The existence of small galaxy-sized gas clouds with no optical counterparts has been seen elsewhere (IC 10: Wilcots & Miller 1998). Thus, it is possible that the southwestern concentration of gas is playing the role of NGC 3077 in the NGC 4449 system rather than just being debris, but this is not certain. In addition, we are still missing the third body, the counterpart to M82 in the M81 system if indeed M82 has played a significant role in producing the large-scale features of the M81 system.

There *is* a galaxy, DDO 125, located only 17 kpc farther south of the southwestern H I concentration. At an apparent separation of 41 kpc from the center of NGC 4449, DDO 125 is located closer than the Magellanic Clouds are to the Milky Way and within 10 km s^{-1} of the same radial speed as NGC 4449. If we assume a relative speed of 100 km s^{-1} in the plane of the sky, DDO 125 and NGC 4449 could have been on top of each other just 0.4 Gyr ago. However, it is doubtful that DDO 125 could have had a significant dynamical effect on NGC 4449. Its dynamical mass, determined from single-dish observations, is only 1×10^9 $M_\odot$ for $D = 3.9$ Mpc (Fisher & Tully 1981); that of NGC 4449 would be of order 10^{10} $M_\odot$ using $W_{20} = 140$ km s^{-1}, for a beamwidth of 21′ (Hunter & Gallagher 1985) and an inclination of 60°, or 10^{11} $M_\odot$ if the velocity field of the streamers can be interpreted as rotation around NGC 4449. Furthermore, DDO 125 itself shows no obvious signs of damage, although the amount of damage in an encounter does depend on the relative rotation and orbit. Finally, DDO 125 has global gas and optical properties that are typical of irregular galaxies (Hunter 1997), although the $M_{\rm H\,I}/L_B$ is at the low end of the distribution. With an H I mass of only 1×10^8 $M_\odot$, it would have to have lost 90% of its H I mass in order to account for all of the mass in the streamers. This seems improbable given the consistency of its other global properties. NGC 4449 is a member of the CVnI "loose" cloud of galaxies (de Vaucouleurs 1975), but other galaxies in the group are 4° or greater than 300 km s^{-1} farther away.

One important feature of NGC 4449 is the counterrotation of the inner and outer gas subsystems. Models have shown that counterrotating gas systems can result from the acquisition of external material. This can occur in a merger (Hernquist & Barnes 1991) or, as discussed above, from the delayed accretion of extended gas (Quinn & Binney 1992). In some cases, however, the counterrotation is only apparent. For example, in M51 the observed counterrotation of gas has been shown to be the result of a warped outer spiral arm that extends into a ring that is inclined to the inner disk (Appleton, Foster, & Davies 1986). The apparent counterrotation results from the viewing angle, although the warping was itself caused by M51's satellite galaxy. In most of these scenarios, therefore, an interaction with another galaxy is involved. Thus, counterrotation, real or apparent, is often a signature of an interaction, even if it is not always the signature of gas capture.

Counterrotation has been seen in numerous galactic systems, and an interesting comparison can be made with the galaxy NGC 4826, in the same group with NGC 4449. Braun et al. (1994) found that the gas of NGC 4826 beyond a 2 kpc diameter region counterrotates relative to the inner gas, both atomic and molecular, and the stars of this galaxy. Fits to the velocity field indicate that gas in the interface is falling into the center as a result of deceleration due to interaction with the stellar disk. However, a difference between NGC 4826's counterrotating systems and those in NGC 4449 is that in NGC 4826, as well as the merger models of Hernquist & Barnes (1991), the two systems are distinct and discontinuous in velocity, while in NGC 4449 the velocities appear to be partly continuous.

If an interaction did occur, with either DDO 125 or a galaxy-sized gas cloud, the interaction could have begun to channel gas into the center of NGC 4449. This is seen in the models of Noguchi (1988). The infalling gas could then account for the bright central concentration of H I, which is composed of large complexes of gas forming a partial ring around the center of the galaxy. In addition, NGC 4449 has a star formation rate that places it at the high end of the distribution for normal irregular galaxies, and an infall of gas could fuel this (Noguchi & Ishibashi 1986). If significant amounts of H I are falling in in coherent clouds, the 2 kpc diameter H I supershell extending from the center of the galaxy to the west (Hunter & Gallagher 1997) could represent a hole that was formed by bombardment of such a cloud rather than the result of energy input from massive stars in the center of the galaxy (see, e.g., Saito et al. 1992).

While the analogy with the M81 system is a compelling argument for NGC 4449's streamers being the result of an interaction, the case is by no means proved, and there is no coherent story yet that covers all of the observations. Modeling specific to the system will be necessary to reconstruct what has happened to NGC 4449 and what role, if any, DDO 125 has played in it. However, we can say that NGC 4449 no longer fits the standard picture of an irregular galaxy quietly evolving in isolation. The presence of extended gas around NGC 4449 may also influence its future evolution, for example, by enhancing its cross section for further collisional interactions.

Although other irregulars are known to have H I extended beyond, and sometimes well beyond, their Holmberg diameters, the extended gas has been mapped in only a few cases as far out, at such a high resolution, as the observations we present here. IC 10 is one such galaxy, and its extended gas also exhibits peculiar structure, although in a very different way compared with NGC 4449 (Wilcots & Miller 1998). The extended H I of DDO 154, on the other hand, appears to be smoothly and regularly distributed (Carignan & Beaulieu 1989). Therefore, while it is clear from a number of surveys (Huchtmeier et al. 1981; Hunter & Gallagher 1985; Hoffman et al. 1996; Broeils & van Woerden 1994; van Zee, Haynes, & Giovanelli 1995) that very extended, moderate column density H I gas like that in NGC 4449 is not common, we do not yet know the frequency or characteristics of this phenomenon in moderate- or low-mass galaxies.

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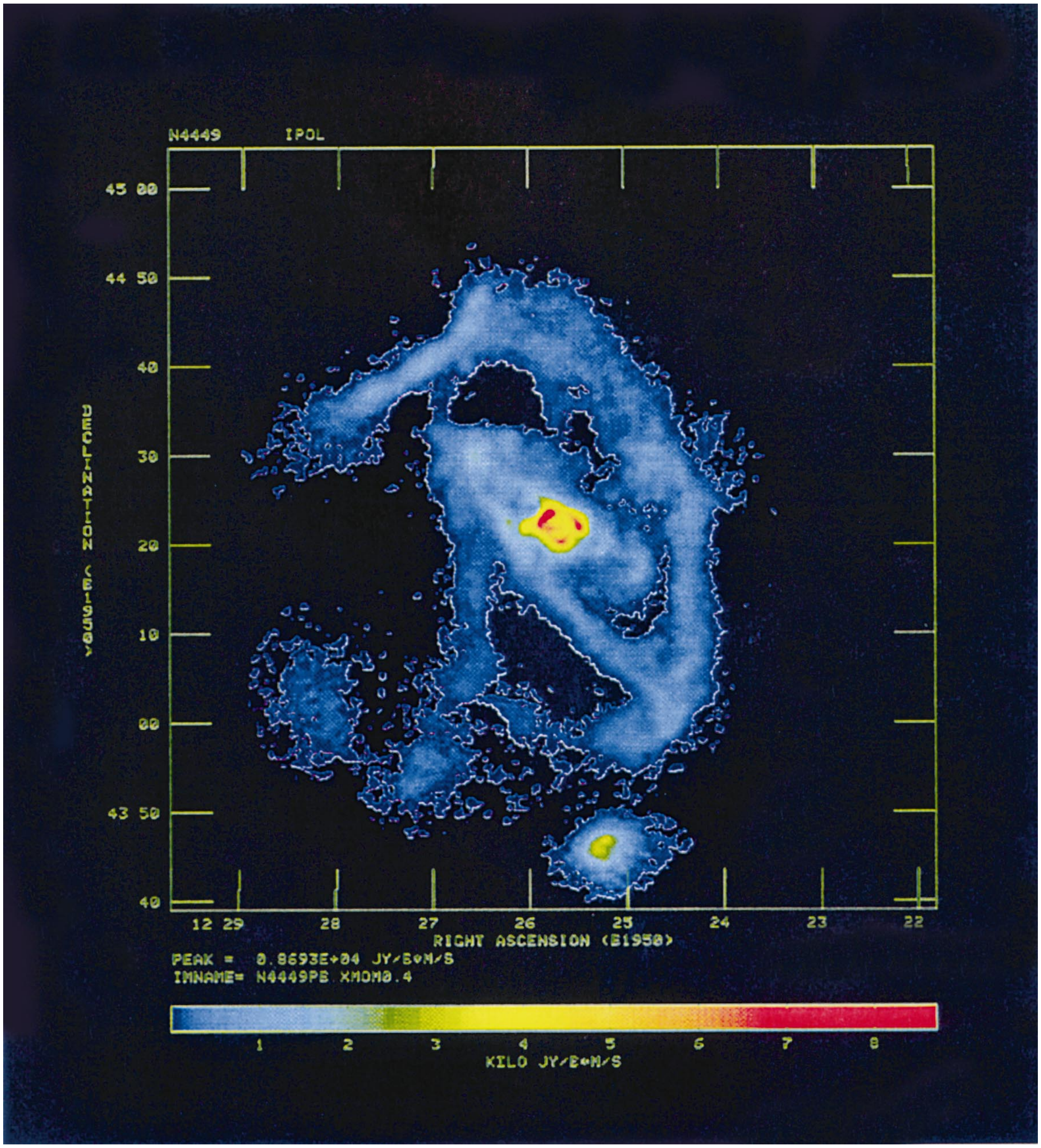

FIG. 1.—Pseudocolor representation of the integrated H I distribution of the gas around NGC 4449. This map was made from a mosaic of nine VLA D-array pointings plus the pointed map of DDO 125, which is the bright object at the bottom edge of the figure.

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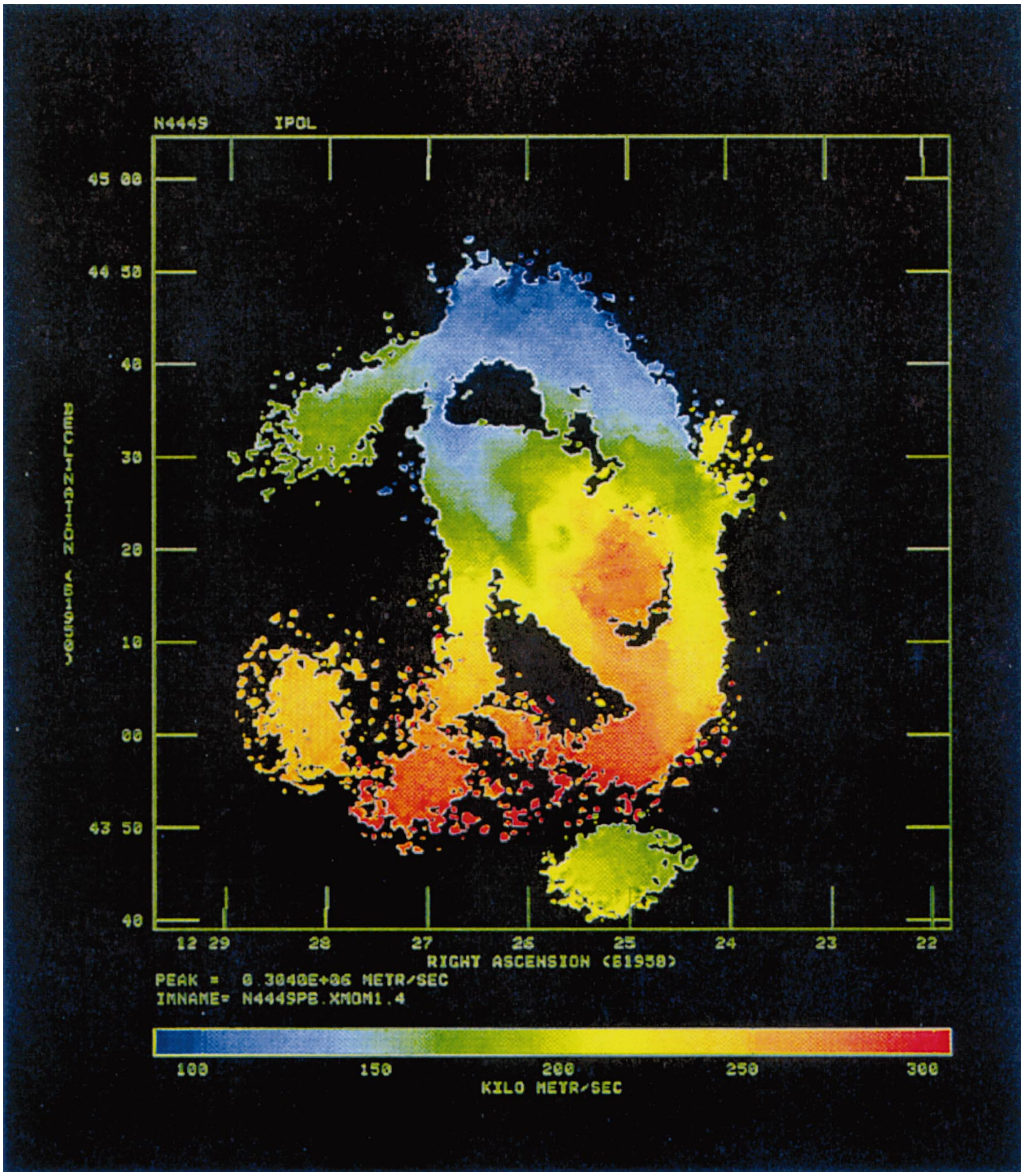

FIG. 3.—False-color depiction of the velocity field of the H I gas around NGC 4449 determined from the D-array mosaic map

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