A Study of the Kinematics of the Peculiar Galaxy Arp 10

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Abstract

We present VLA H I and optical spectra of the peculiar galaxy Arp 10. Originally believed to be an example of a classical colliding ring galaxy with multiple rings, the new observations show a large disturbed neutral hydrogen disk extending 2.7 times the diameter of the bright optical ring. We also present evidence for optical shells or ripples in the outer optical isophotes of the galaxy reminiscent of the ripples seen in some early type systems. The H I disk comprises of two main parts: a very irregular outer structure, containing peculiar loops and filaments and a more regular inner disk associated with the main bright optical ring. In both cases, the H I structures do not exactly trace the optical morphology. This effect is most apparent in the outer parts, where the HI emission resembles the H I loops seen in some shell elliptical galaxies. Even the inner H I disk does not correspond well morphologically nor kinematically to the optical rings. These peculiarities lead us to believe that the potential in which the H I disk resides is significantly out of equilibrium – a situations which would inherently produce rings of star formation. We suggest that Arp 10 is either i) the late stages of a merger between a large H I rich disk and an SO galaxy or ii) the final stages in the formation of a single gas-rich disk system.

Introduction

Arp 10 (= VV 362) is a galaxy containing a bright ring, an off-center nucleus and a faint bar. These features can be easily detected in the photograph presented in the Arp Atlas of Peculiar Galaxies (Arp 1966), suggesting that Arp 10 may be a colliding system. Recent deep CCD imaging of the galaxy in Hα and R-band by Charmandaris, Appleton and Marston 1993, hereafter CAM, revealed, in addition to the bright ring, an very small inner ring and traces of outer ring arcs. It also provided evidence for threshold behavior of the star formation rate along the rings. In that paper we suggested that Arp 10 may be an example of a collisional ring galaxy, in which rings are produced as a result of the passage of a small galaxy through the center of a larger rotating disk (Lynds and Toomre 1976). Our latest spectral observations (Charmandaris and Appleton 1995; hearafter C&A) indicate that the plausible elliptical "companion" suggested by CAM is infact a background galaxy with a redshift of z=0.089 ($v = 26,680\,\mathrm{km\,sec^{-1}}$).

Deep broad-band imaging by Appleton and Marston (1995) now show that, in addition to the bright inner rings, the galaxy exhibits faint optical structure reminiscent of shells or "ripples" seen around some early type galaxies (e.g. Schweizer and Seitzer 1988). A reproduction of a B-band image of Arp 10 is shown in Figure 1. The fact that Arp 10 shows both "ripples" and rings suggests a formation history which may be intermediate between a classical ring galaxy and a merger/mass transfer event which is thought to responsible for most "ripples" or shells (Quinn 1984, Dupraz & Combes 1986, Hernquist and Quinn 1989). The discovery of an extra-nuclear knot by CAM $5''$ to the south -west of the nucleus of Arp 10 lends further support to the idea that Arp 10 is some form of merging system, since the knot might be the nucleus of a second galaxy. The single dish H I spectrum of the galaxy obtained by Sulentic and Arp (1983; hereafter SA) using the Arecibo radio telescope, exhibits the typical two-horned profile of a rotating planar disk. It was assumed that such a disk would be associated with the bright optical ring. The study of the morphology and kinematics of H I in this system is therefore of considerable interest in the search for a complete explanation for the formation of rings and shells, but also for the ultimate fate of gas in such systems.

Arp 10 was chosen as part of a larger study of the dynamics of ring systems (See Appleton and Struck-Marcell, 1995 for review). In order to study kinematics of the system we obtained medium resolution H I observations of Arp 10 using the C-array of the Very Large Array. The observations were made on December 4 1994, using all 27 telescopes in the C-array of the VLA. We used a bandwidth of 3.125 MHz centered at 9,104 $\mathrm{km\,s^{-1}}$, the heliocentric optical velocity of the galaxy. The correlator was set in the 2AC mode with on-line hanning smoothing and 64 channels. This provided a frequency separation of 48.8 kHz per channel, which corresponds to 10.94 $\mathrm{km\,s^{-1}}$ in the rest-frame of the galaxy using the optical definition of redshift. The velocity coverage of our observations was 689 km $\mathrm{s^{-1}}$. A total of 4 hours 53 min was spend on source. Flux and phase calibration was achieved using the sources 3C48 and 0202+149 (1950) respectively. The data reduction was performed using AIPS. We also made longslit spectrophotometric observations of the galaxy using the Goldcam spectrograph at the KPNO 2.1m telescope, on the nights of November 28,29 1992 and January 30, 1995. The spatial resolution of the spectra was 1.56 arcsec $\mathrm{pixel^{-1}}$ and the dispersion 1.52 Å $\mathrm{pixel^{-1}}$. A detailed analysis of those observations is presented by C&A.

Global Profile and H I Distribution

The integrated H I profile of Arp 10, presents a well defined two-horned profile of a rotating disk. The integrated flux density $\int S(V)dV$ detected by SA using Arecibo was 3.1 $\mathrm{Jy\,km\,s^{-1}}$. Our observations detected 2.75 $\mathrm{Jy\,km\,s^{-1}}$ which accounts for 89% of the total emission quoted by SA. There is a small asymmetry in our profile with the left (low velocity) horn broader and with smaller peak flux value than the right (high velocity) one. This is opposite to the one appearing in the spectrum of the single dish observations (Figure 1 of SA). These differences, though small, may relate to the fact that the C-array is not sensitive to all the flux in the source. We are clearly missing approximately 10% of the flux seen in the single dish data. On the other hand, small differences in the pointing of the Arecibo telescope relative to the kinematic center of the galaxy could account for the differences in the line shapes. Assuming that the gas is optically thin, we calculated the total H I mass M_H and the integrated flux F_H. All derived properties for Arp 10 are presented in Table 1.

The integrated H I distribution of Arp 10 is presented in Figure 2. We observe that the hydrogen emission is very extended and it is distributed over a roughly elliptically-shaped area (see Table 1). The HI dimensions are 2.7 times the diameter of the bright ring seen in the Arp(1966) Atlas (Ring 2 of CAM) and extends well outside the dimensions of the faint optical "ripples" seen in Figure 1. The H I emission exhibits strong peaks in two areas, one southeast and northwest of the nucleus. The north-western peak seems to coincide with the part of Ring 2 which also displays strong Hα emission (CAM).

The Kinematics of the H I Gas

A careful analysis of the channel maps of the H I distribution galaxy (C&A) revealed a loopy and peculiar nature of the H I features. There is a lack of obvious correlation between the H I and optical structures (except for the northern end of the bright ring and the eastern "arm"). However, it is perhaps surprising to find that the overall velocity field of the system looks, superficially, like a normal rotating disk. The mean velocity field of the H I emission is shown in Figure 3. The overall impression is that of a single coherent rotating disk of H I with a kinematic major axis close to a PA=0°. The northern end of kinematic major axis shows contours of increasing velocity with radius, symptomatic of a solid-body rotation curve, whereas the southern end of the galaxy shows a turn-over on the peak velocity and a slow decline thereafter with radius. A close inspection of Figure 3 will show that deviations from this simple picture are apparent at the approximate radius of the bright ring and in the outer regions of the disk, especially to the NE and the SW. The magnitude of the deviations are approximately 30 $\mathrm{km\,s^{-1}}$. It was clear to the authors that the reason for the change in the isovelocity field at this radius is due to the shift in emphasis from the loopy outer structures, which have an approximate north-south kinematic axis, to an inner structure dominated by emission from the northern end of the ring and the inner stem of the eastern "arm". However, as Figures 5a,b of C&A show, the emission in both regions is far from normal for a simple rotating disk.

A Comparison between the Optical and H I Velocities

In Figures 4a and b, we present position-velocity diagrams through the center of the galaxy along both the major (PA=130°) and minor axes of the rings respectively. The solid lines show the H I velocities and the black dots show velocities measured in the H II regions using our KPNO spectra. Within the errors of the optical observations (30km s^{-1}, there is generally good correspondence between the optical and H I velocities for the major axis slice. There is a slight suggestion that the optical velocities are systematically higher by 50 km s^{-1} than those obtained in the H I. Our average optical velocity for the galaxy is 9160 km s^{-1} compared with the H I velocity of 9108km s^{-1}. This velocity difference could be explained by a slight misalignment between the slit position and the nucleus during the optical observations, or alternatively could reflect a real difference between the velocity of the optical nucleus and the H I disk. The asymmetry in the shape of the rotation curve is obvious (Fig. 4a). The north-western disk shows a rising rotation curve, whereas the south-eastern side of the galaxy flattens out at a radius of about $10''$. The position-velocity slice along the minor axis (Fig. 4b) is also peculiar in that large velocity gradients are observed (of order 150 km s^{-1} over an angular scale of $10''$). The optical velocities in the south-west quadrant of the galaxy seem to be higher than those found in the H I, even taking into account the systematic effect discussed above.

Conclusions - Arp 10 : A Major Merger or a Disk in Formation ?

Arp 10 is not a normal galaxy. Optically, its appearance alone placed it in the peculiar galaxy catalogs of Arp and VV. The new H I observations and analytical modeling of the velocity field presented in this meeting, show that Arp 10 is not a classical ring galaxy. The kinematics of the HI gas may be explained if Arp 10 is merger of a large H I disk and an S0 galaxy similar to the ones of Schweizer & Seitzer (1988). Such and interaction could cause the disturbed morphology of the outer H I disk. The nucleus of the S0 would create a perturbation to the center of potential of the disk leading the formation of the optical rings and outer shells. The observed extra-nuclear knot (CAM) may be this remnant nucleus. Such a scenario, though plausible, could be refined if we obtain information on the kinematics of the inner ring and exta-nuclear knot. Higher resolution spectra taken along different position angles in the system would be be highly desirable.

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Table 1: Properties of Arp 10

$\alpha(1950)$	$2^{\mathrm{h}}15^{\mathrm{m}}48.9^{\mathrm{s}}$
$\delta(1950)$	$+5^{\circ}25'26.0''$
Distance	121 Mpc
Optical diameter	$5.6'' = 3.2$ kpc
Bright Ring	$43.0'' = 25.2$ kpc
Outer Isophotes	$80'' = 46.9$ kpc
HI dimensions	$120'' \times 90'' = 70.4 \times 52.7$ kpc
V_{opt}	9160 ± 30 km s^{-1}
V_{HI}	9108 ± 10 km s^{-1}
$\Delta V_{1/2}$	249 ± 15km s^{-1}
$\Delta V_{1/5}$	272 ± 15km s^{-1}
F_H	6.48×10^5 Jy km s^{-1}
M_H	$9.5 \times 10^9\, M_{\odot}$
$M_T = \frac{\Delta V_{\frac{1}{2}}^2 R_{HI}}{G}$	$4.9 \times 10^{11}\, M_{\odot}$
M_H/M_T	0.019