THE NEUTRAL HYDROGEN DISTRIBUTION IN LUMINOUS INFRARED GALAXIES

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1. Introduction

Although there is strong evidence that the luminous ($L_{IR} > 3 \times 10^{11} L_\odot$; H_o=75) and ultraluminous ($L_{IR} > 10^{12} L_\odot$) infrared galaxies result from the merger of two spirals (Sanders *et al.* 1988, Scoville *et al.* 1991), it is somewhat surprising that the optical morphology of these systems differs from the classical double-tailed morphology of merging disks described by Toomre & Toomre (1972) and illustrated by the sequence of 11 disk-disk systems in progressively advanced stages of merging known as the "Toomre Sequence" (Toomre 1977)[1]. In particular, the luminous IR galaxies as a class tend to exhibit shorter and/or more poorly defined tidal tails than the systems from Toomre's Sequence (Hibbard 1995). Similarly, optically selected interacting samples (including the Toomre Sequence) often have IR properties that are closer to those of isolated spirals than the ultraluminous IR galaxies (see Table 1).

These differences may simply reflect the short lived nature of the luminous IR phase, the rarity of long tails in disk-disk encounters, and/or a special viewing perspective for the Toomre Sequence objects. However they may also indicate necessary prerequisites for triggering luminous infrared

[1]This sequence includes the best studied and strongest cases for disk-disk mergers, such as "The Antennae" (N4038/9), "The Mice" (N4676), and "The Atoms for Peace Galaxy" (N7252).

TABLE 1. **Comparison between IR and Optically Selected Mergers**

Property	IRAS BGS $\log(L_{IR}/L_\odot)$>12	IRAS BGS $\log(L_{IR}/L_\odot)$>11.5 Distance<100 Mpc	Toomre Sequence of Ongoing Mergers in the NGC
Sample Size	10	8	10
Average Redshfit	15740±5770km s^{-1}	5520±1250km s^{-1}	4760±2170km s^{-1}
$< L_{IR} >$	$(2\pm1)\times10^{12} L_\odot$	$(6\pm4)\times10^{11} L_\odot$	$(2\pm1)\times10^{11} L_\odot$
$< L_{IR}/L_B >$	45±21	25±24	5±5
$< M_{H_2} >$	$(3\pm2)\times10^{10} M_\odot$	$(2\pm1)\times10^{10} M_\odot$	$(1\pm1)\times10^{10} M_\odot$
$< M_{H_2}/L_B >$	$0.9\pm0.6\ M_\odot L_\odot^{-1}$	$0.6\pm0.5\ M_\odot L_\odot^{-1}$	$0.4\pm0.2\ M_\odot L_\odot^{-1}$
$< L_{IR}/M_{H_2} >$	$78\pm53\ L_\odot M_\odot^{-1}$	$48\pm21\ L_\odot M_\odot^{-1}$	$18\pm16\ L_\odot M_\odot^{-1}$
Avg. No. of Tails	0.7±0.7	0.8±0.7	1.7±0.4
Average tail length:			
— Optical	32±6 kpc	30±3 kpc	53±23 kpc
— H I	—	63±47 kpc	88±47 kpc

activity in mergers, such as specific orbital geometries or Hubble types for the progenitors (Hibbard 1995). In an effort to clarify this matter, we have mapped the neutral hydrogen distribution in a sample of seven nearby ongoing mergers which are luminous in the infrared. We compare these observations with similar data on the less IR luminous mergers of the Toomre Sequence (Hibbard & van Gorkom AJ, in press; Mahoney, van der Hulst & Burke, in preparation; English, in preparation).

2. Observations and Results

The Infrared selected systems were chosen from the IRAS bright galaxy sample (BGS) list presented by Sanders *et al.* (1991). We observed 8 systems within 150 Mpc with $L_{IR} > 3\times10^{11}L_\odot$ and L_{IR}/L_B >10. The neutral hydrogen data were collected in 1994 and 1995 using the Very Large Array in its spectral line mapping mode. Each galaxy was observed in the C- and D-array configurations. Final sensitivities were a few 10^{19}cm^{-2} at resolutions of $\sim20''$, with a velocity spacing of $\sim$11 km s^{-1}. All but one of the systems (Mkn 231) were detected in emission. The results are presented in **Figs. 1–7**, and described briefly in the accompanying captions.

There are a number of similarities between the tidal morphologies of the IR and optically selected mergers. Most of the systems (5/7) require two atomic gas-rich progenitors, and we frequently (3/7) discover massive gaseous tidal features ($M_{HI} > 10^9 M_\odot$) which extend well beyond the end of the optical tails. In contrast to what was found optically, we find a much less significant difference in the average H I tail lengths of the two samples (see Table 1).

The major difference is that a broader range of encounter spin orientations are represented in the IR sample. There are prograde-prograde encounters (N2623, IC 883), prograde-retrograde encounters (Arp 299 and N1614) and a retrograde-retrograde encounter (VV 114). The systems from the Toomre Sequence, on the other hand, experience prograde-prograde encounters. (The spin geometries of Arp 220 and Mkn 273 from the IR sample and N3921 from the optical sample cannot be constrained due to the lack of two distinct kinematic systems in H I).

It therefore appears that the IR luminousity criterion selects for a broader range of encounter geometries than found for the optically selected systems of the Toomre Sequence. This fact combined with a more favorable viewing geometry for the Toomre Sequence objects can probably account for the differences reported in Table 1. However, it would be reassuring to find more IR luminous mergers with long optical tails and to show that apparently short and/or poorly defined optical features are the norm in merging encounters. An imaging study is underway to address these points.

References

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Figure Captions: The H I distribution (contours) superimposed upon an optical image (greyscales) of each of the systems in this study. The H I contours are drawn at (5,10,20,40,80,160) $\times 10^{19}$cm^{-2}. All systems show central H I absorption against a radio continuum source, which is indicated by the dashed contours. Because of the central absorption, all H I mass estimates in the following are lower limits. A white bar indicates 20 kpc. Optical images are from the digitized Palomar Sky Survey (A299, N1614, VV114 and IC883), or 300 sec R-band images from the UH 88″ telescope (A220 and Mk273) or the KPNO 2.1 m telescope (N2623).

FIG. 1: Arp 220 [log($L_{IR}/L_\odot$)=12.18]. There is $2\times10^9 M_\odot$ of neutral hydrogen detected in emission from the outer regions of this ultraluminous IR object. It is not clear whether these features are a single continuous feature, or two separate features. The kinematics of the gas to the west of the main body are continuous with the gas directly to the north, suggesting that they are part of a continuous structure which is broken by the northern optical tidal plume. There is a clear anti-correlation between the observed

H I and the optical tidal features, especially near the northern plume.
FIG. 2: Arp 299 [log($L_{IR}/L_{\odot}$)=11.91]. The H I morphology is radically different from the starlight, with a narrow tidal filament without any apparent optical feature stretching 150 kpc to the north and containing $2{\times}10^9 M_{\odot}$ of atomic gas. This filament suggest a very old encounter age ($\sim$750 Myr) for this very young starburst ($\sim$ 20 Myr; Augarde & Lequeux 1985, A&A, 147, 273). Back in the main body, there is over $4{\times}10^9 M_{\odot}$ of H I associated with both disks, the majority of which is associated with the NE disk. The sense of rotation derived from the plume is opposite that derived from the ionized gas in the NE disk (Hibbard, Bland-Hawthorn, & Tully, in preparation), suggesting a prograde-retrograde encounter.
FIG. 3: NGC 1614 [log($L_{IR}/L_{\odot}$)=11.61]. Once again there is a long tidal filament ($10^9 M_{\odot}$, 85 kpc) without an optical counterpart and not connecting back in any obvious way to any of the optical tidal features. There is at least $10^9 M_{\odot}$ of H I associated with the main body. The rotation of the ionized gas in the nearly face-on disk (Neff *et al.* 1990, AJ, 99, 1088) gives an opposite sense of motion than for the H I tail, again suggesting a prograde-retrograde encounter.
FIG. 4: VV 114. [log($L_{IR}/L_{\odot}$)=11.62]. The H I kinematics suggest two separate components rotating in the same direction. The lack of any tail-like features and the fact that so much gas ($>8.4{\times}10^9 M_{\odot}$!) remains close to the remnant suggests a retrograde-retrograde encounter between two gas-rich disks. There is an optical shell-like feature extending to the north anticorrelated with the gas in this region.
FIG. 5: Mkn 273 [log($L_{IR}/L_{\odot}$)=12.14]. This system has a single gas rich tail extending to the south with smooth kinematics, suggesting at least one gas rich progenitor experiencing a prograde encounter. There is a second optical tidal feature extending to the northeast from which we detect no H I, although this may be due to its more face-on orientation.
FIG. 6: IC 883 [log($L_{IR}/L_{\odot}$)=11.60]. The H I emission from this system is confined mostly to the crossed optical tails. Both tails have similar quantities of atomic gas ($1.5{\times}10^9 M_{\odot}$ in the east, $1.1{\times}10^9 M_{\odot}$ in the west) and similar lengths (30 kpc), and move in opposite directions, suggesting a merger involving two prograde gas-rich disks.
FIG. 7: NGC 2623 [log($L_{IR}/L_{\odot}$)=11.55]. This, the least IR luminous of the IR bright sample also happens to be the most IR luminous system in the Toomre Sequence. The tidal features are very similar to most of the galaxies in that sequence, with two gas-rich tails ($10^9 M_{\odot}$ in the east, $3.4{\times}10^9 M_{\odot}$ in the west) moving in opposite directions, again suggesting a merger of two prograde gas-rich spirals. The H I in the western tail extends beyond the end of the optical light by a factor of three in projected distance, to a total length of 85 kpc.

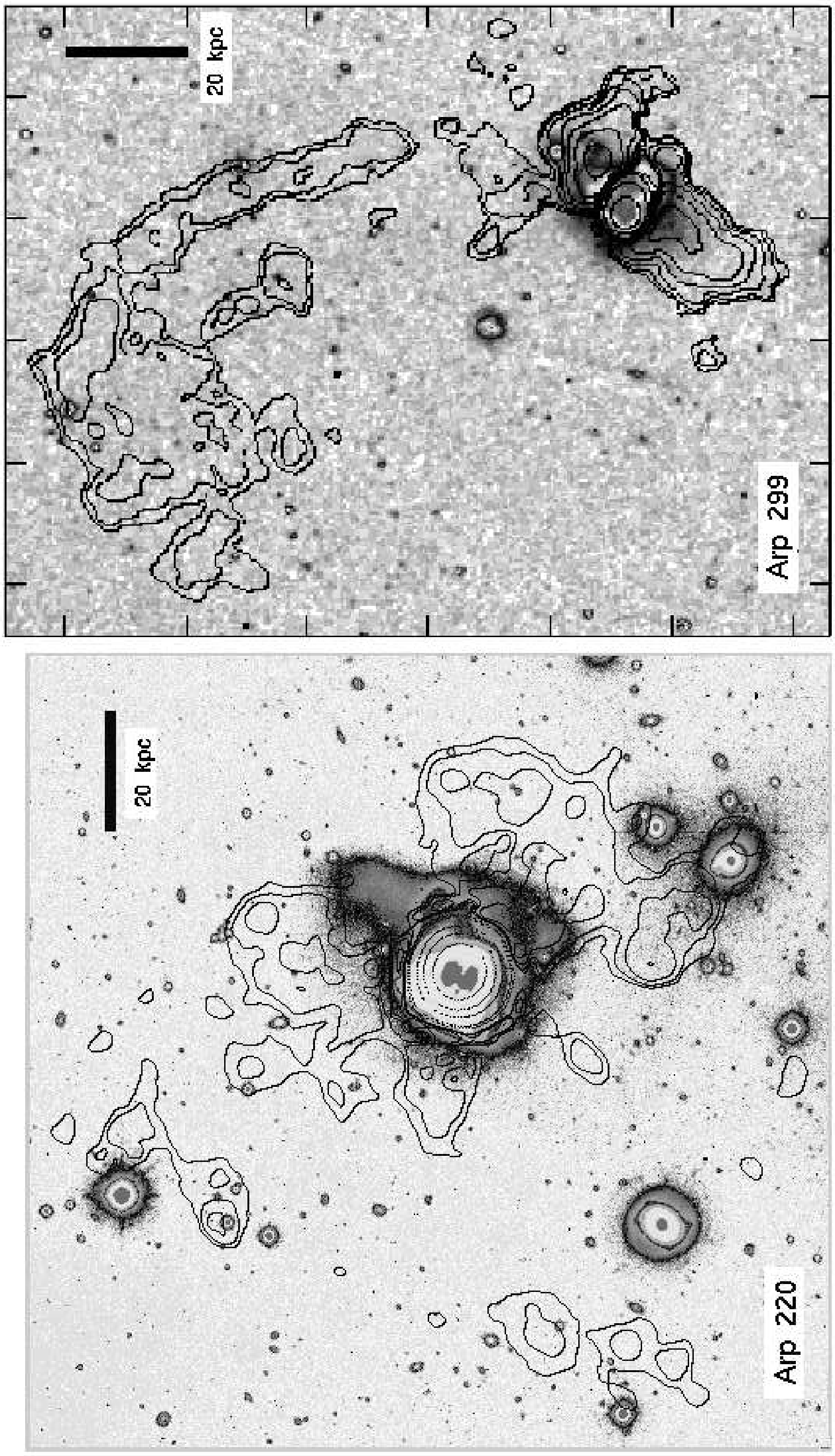

Figure 1. Figures 1 and 2.

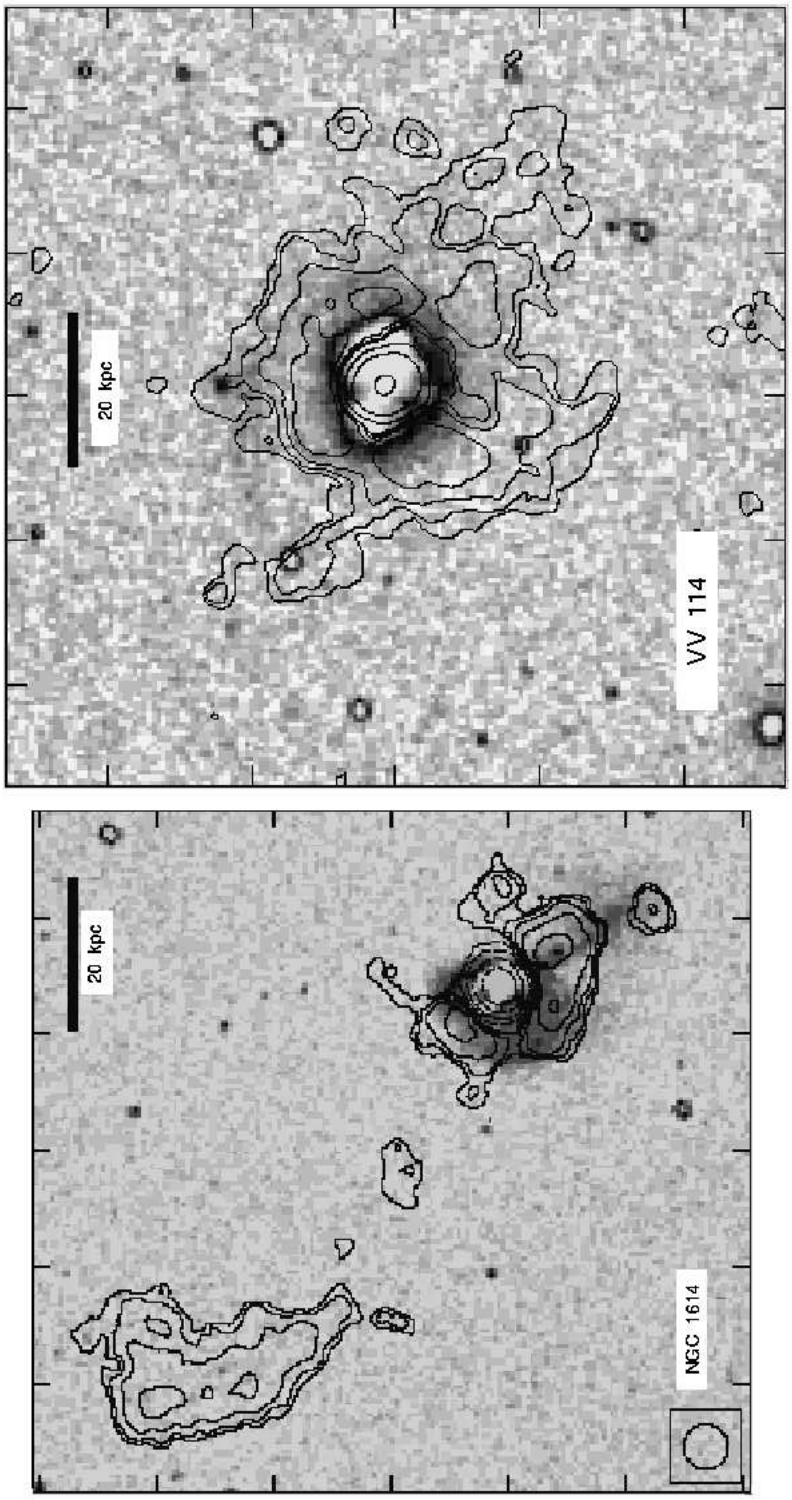

Figure 2. Figures 3 and 4.

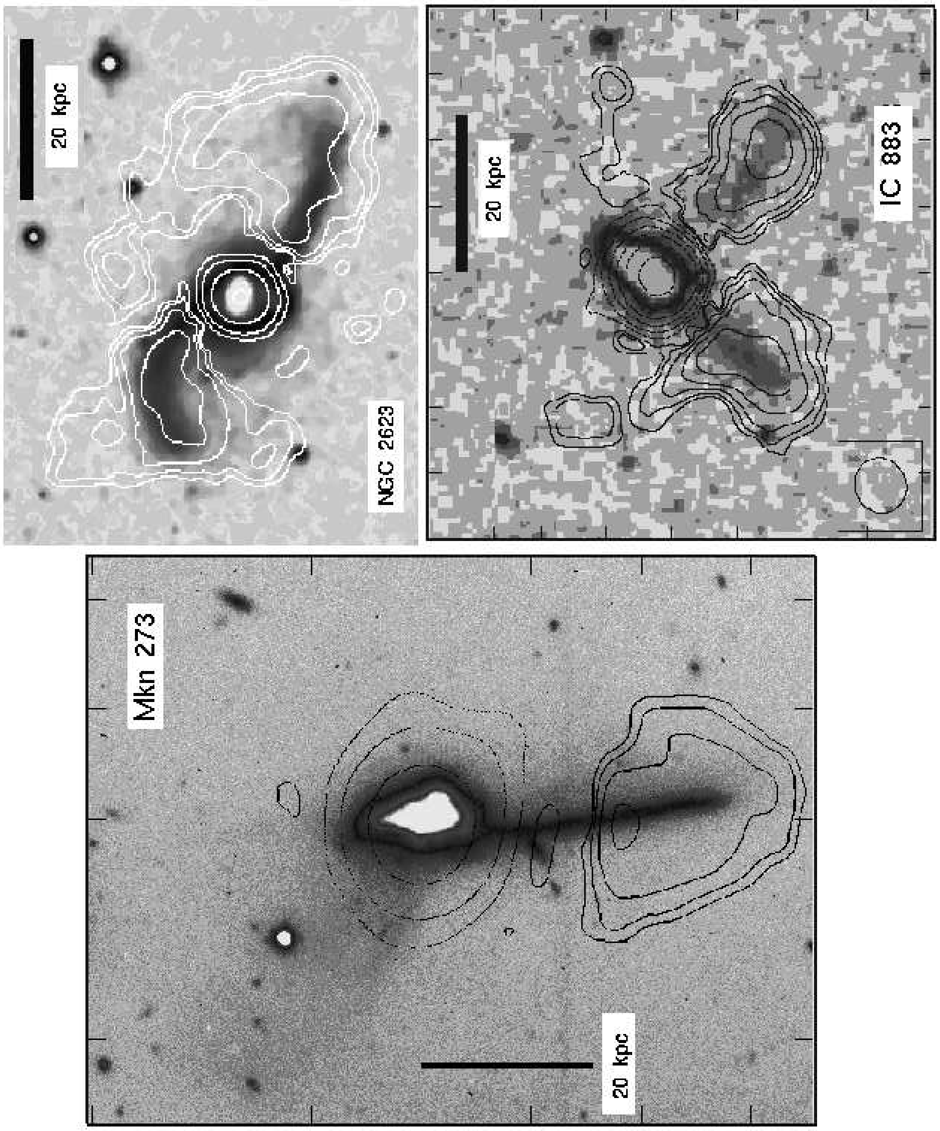

Figure 3. Figures 5–7.