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HIPASS DETECTION OF AN INTERGALACTIC GAS CLOUD IN THE NGC 2442 GROUP

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ABSTRACT

We report the discovery from the H I Parkes All-Sky Survey (HIPASS) of a gas cloud associated with the asymmetric spiral galaxy NGC 2442. This object, designated HIPASS J0731−69, contains $\sim 10^9\ M_\odot$ of H I, or nearly one-third as much atomic gas as NGC 2442 itself. No optical counterpart to any part of HIPASS J0731−69 has yet been identified, consistent with the gas being diffuse and its streamlike kinematics. If the gas in HIPASS J0731−69 was once part of NGC 2442, then it was most likely a fairly recent tidal encounter with a moderately massive companion that tore it loose, although the possibility of ram-pressure stripping cannot be ruled out. This discovery highlights the potential of the HIPASS data for yielding new clues to the nature of some of the best-known galaxies in the local universe.

Subject headings: galaxies: individual (NGC 2442) — galaxies: interactions —
galaxies: intergalactic medium — radio lines: galaxies

1. INTRODUCTION

The nearby southern galaxy NGC 2442 ($V_\odot = 1449$ km s^{-1}) provides a striking example of well-developed but asymmetric spiral arms (Fig. 1; see also panel 207 of Sandage & Bedke 1994). The northern arm bends back on itself quite tightly and is sharply bisected by one continuous dust lane, while the southern arm is shorter, more open, and crisscrossed by numerous dust features. There have been several attempts to ascribe this asymmetry to a past interaction with a neighboring galaxy, but no clear culprit has yet emerged. Sandage & Bedke (1994) suggested interactions with the nearby E0 galaxy NGC 2434 ($V_\odot = 1390$ km s^{-1}, separation 16′.8) or perhaps the more distant spiral NGC 2397 ($V_\odot = 1363$ km s^{-1}, separation 85′); Elmegreen et al. (1991) also blamed NGC 2434, but Mihos & Bothun (1997) argued on the basis of its proximity and slightly disturbed morphology that the small SB0/a galaxy AM 0738−692 is a more likely candidate. In an H I aperture synthesis study of NGC 2442 with the Australia Telescope Compact Array (ATCA), Houghton (1998) failed to detect any H I associated with AM 0738−692, but she did find evidence of weakly disturbed H I in the irregular galaxy ESO 059-G006 ($V_\odot = 1346$ km s^{-1}), located some 17′.1 south of NGC 2442.

A deep optical image (Fig. 2) showing NGC 2442 and most of the galaxies mentioned above has been produced by adding three contrast-enhanced IIIa-J plates from the UK Schmidt Telescope. This image also highlights a diffuse extension of the northern arm, which extends almost halfway toward ESO 059-G006 before becoming indistinguishable from the diffuse Galactic reflection nebulosity that pervades the field.

Distance estimates in the literature for NGC 2442 range from 14 Mpc (Sérsic & Donzelli 1993) to 17.1 Mpc (Tully 1988). We adopt $D = 15.5$ Mpc (1′ = 4.5 kpc) in what follows. Garcia (1993) assigns only three other galaxies to the group (LGG 147) that already includes NGC 2442: NGC 2397, NGC 2434, and PGC 20690 (AM 0720−723), a Magellanic irregular some 3°.5 south of NGC 2442. The same four galaxies were similarly grouped together by Tully (1988) and designated 53-17. However, in light of the above discussion and several recent redshift determinations, it is clear that the NGC 2442 group is somewhat more populous than once thought. Table 1 lists all the galaxies within 90′ (400 kpc projected distance) of NGC 2442 whose redshifts are known. The galaxies ESO 059-G010 and ESO 059-G007 are probably also close neighbors, but no redshifts are available yet.

In this paper, we report the discovery of significant amounts of diffuse H I to the northwest of NGC 2442 and discuss how this may help shed new light on the nature of its unusual appearance.

2. OBSERVATIONS AND RESULTS

The H I Parkes All-Sky Survey (HIPASS) is a blind H I survey of the entire local southern sky ($\delta < 2°$, $-1200 < V_\odot < 12{,}700$ km s^{-1}), carried out between 1997 February and 2000 March. The survey uses a 13 beam receiver mounted on the Parkes 64 m telescope to scan the sky

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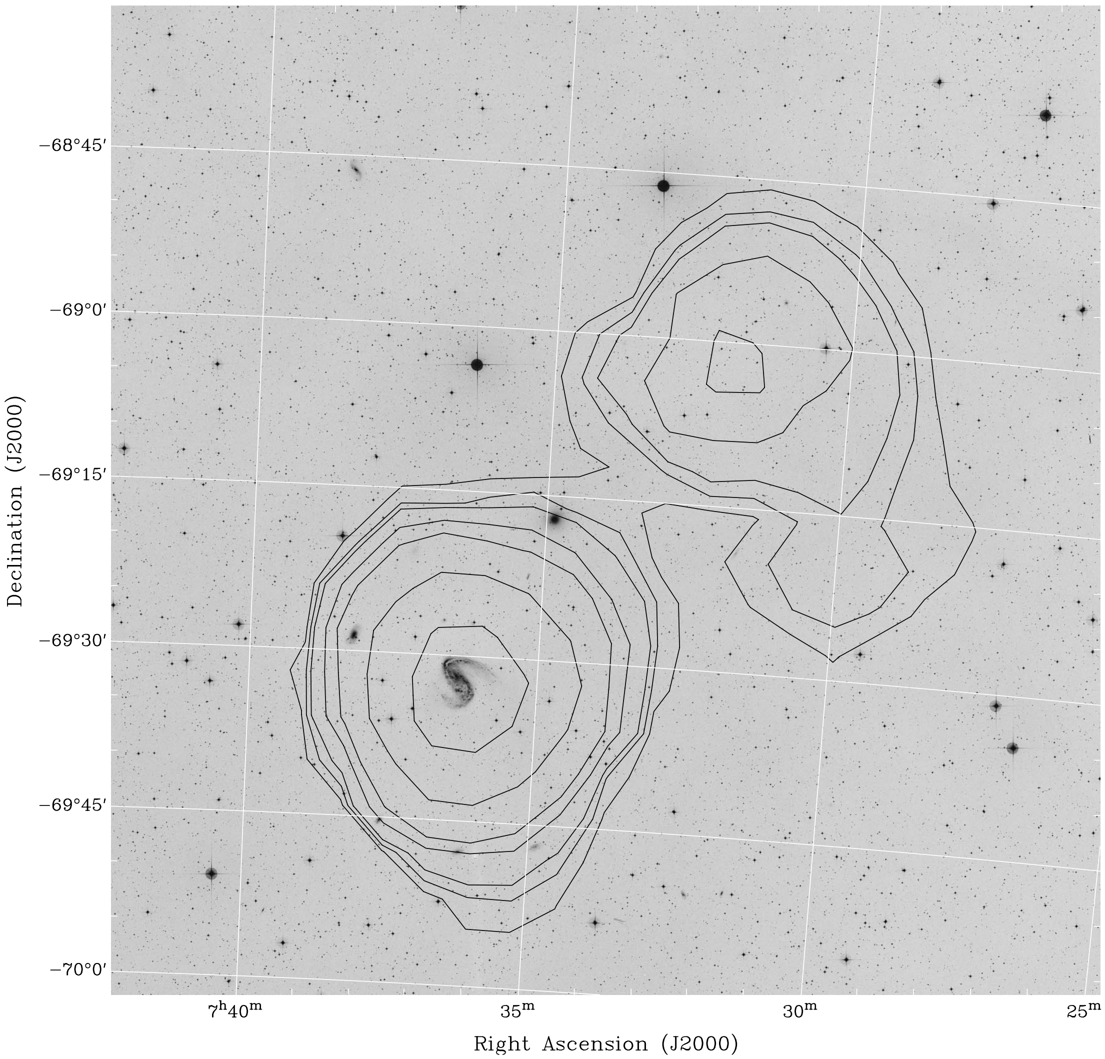

FIG. 1.—Integrated H I column density contours from the HIPASS observations of the region around NGC 2442, overlaid on a *B*-band image from the DSS, together with grid lines of constant right ascension and declination. Contours are plotted at levels of 0.01, 0.02, 0.03, 0.06, 0.09, 0.2, and 0.4 $M_\odot$ pc^{-2} (multiply by 1.25×10^{20} to get equivalent number of H atoms cm^{-2}). Note the disturbed appearance of the spiral arms in NGC 2442, the absence of any significant H I contribution from NGC 2434 (*just left of center*), and the lack of a bright optical counterpart to HIPASS J0731−69.

TABLE 1

NEIGHBORS OF NGC 2442 WITH KNOWN REDSHIFT

Galaxy	α (J2000)	δ (J2000)	$V_\odot$ (km s^{-1})	Source
NGC 2442..........	07 36 23.9	−69 31 48	1475	1
LEDA 100030	07 36 40.7	−69 26 39	1331	2
AM 0738−692......	07 38 11.8	−69 28 27	1529	1
AM 0737−691......	07 37 12.6	−69 20 31	1456	2
NGC 2434..........	07 34 51.4	−69 17 01	1390	3
ESO 059-G006......	07 34 51.1	−69 46 49	1346	2
ESO 059-G012......	07 38 31.8	−68 46 16	1323	4
NGC 2397..........	07 21 20.8	−69 00 07	1363	5
NGC 2397A.........	07 21 56.3	−68 50 45	1392	6

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

REFERENCES.—(1) Mihos & Bothun 1997; (2) Houghton 1998; (3) de Vacouleurs et al. 1991; (4) di Nella et al. 1996; (5) Mathewson, Ford, & Buchhorn 1992; (6) Koribalski et al. 2001.

in 8° strips of declination, revisiting each point on five separate occasions, for an effective integration time of 460 s beam^{-1}. Full details of the multibeam receiver system, survey strategy, and on-line data analysis can be found in Staveley-Smith et al. (1996) and Barnes et al. (2001). The HIPASS data cubes[13] used in this analysis have a final beamwidth of $\sim 15'.5$, a velocity resolution of 18 km s^{-1}, an rms noise level of ~ 13 mJy beam^{-1}, and a spatial pixel size of 4′.

One of the first major data products to emerge from HIPASS is the HIPASS Bright Galaxy Catalog (Koribalski et al. 2001). In the course of measuring the centroid, total flux, and extent of H I emission from the 1000 brightest galaxies in the HIPASS data, we noticed an unusual exten-

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[13] Spectra from the HIPASS data, gridded at 8′ intervals, are now publicly accessible from http://www.atnf.csiro.au/research/multibeam/release/.

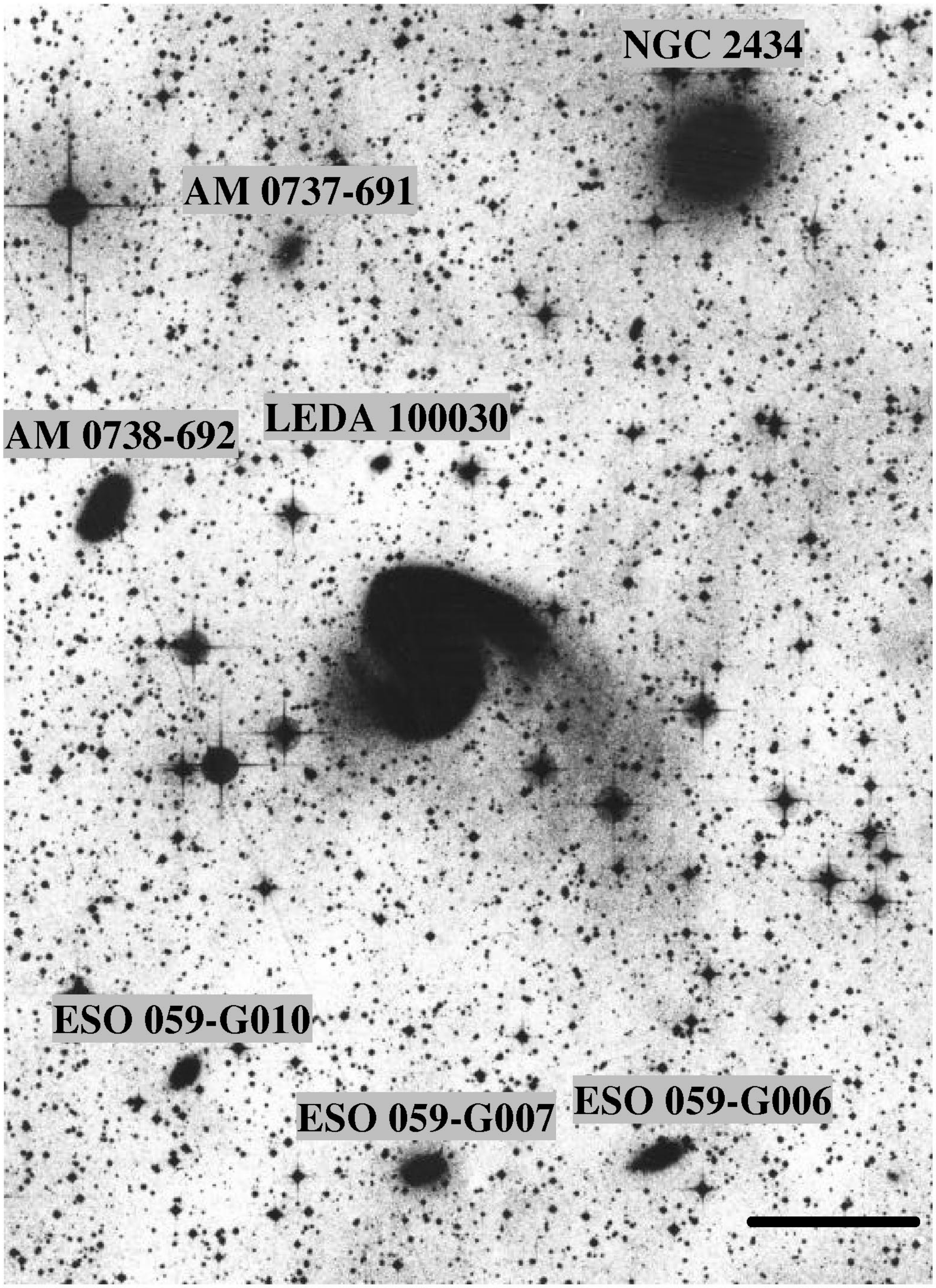

FIG. 2.—Deep optical image of the field immediately surrounding NGC 2442, obtained by summing three blue photographic plates from the UK Schmidt Telescope in the manner outlined by Malin (1981). Comparison with the surface photometry of Sérsic & Donzelli (1993) indicates that the faintest structures visible have a surface brightness of $B \sim 28$ mag arcsec^{-2}. With the exception of NGC 2442 at the center, all galaxies listed in Table 1 that are visible in this image are identified by a label immediately above each one. The solid bar at lower right is 5′ in length.

sion to the integrated intensity (zero moment of the H I data cube) image of NGC 2442, with no obvious optical counterpart (Fig. 1). The peak H I column density in this region is just 0.1 $M_{\odot}$ pc^{-2}, or 1.3×10^{19} cm^{-2}. In accordance with the IAU standard, we assign this new object the provisional designation HIPASS J0731−69.

From an analysis of the zero-moment map as well as the total H I profile (Fig. 3), we find this new source to have a flux integral of 18 ± 3 Jy km s^{-1} (see Barnes et al. 2001 for a discussion of the uncertainties in total fluxes from the HIPASS data). Although the H I profile is somewhat asymmetric (and most unlike the "double-horned" or Gaussian profile expected of a spiral or a dwarf galaxy), we derive a heliocentric velocity for the peak of the line emission of 1481 ± 18 km s^{-1} and a profile width at 20% of the peak intensity, $W_{20} = 270 \pm 60$ km s^{-1}. For comparison, the equivalent HIPASS parameters for NGC 2442 itself from a robust moment analysis and from the H I pro-

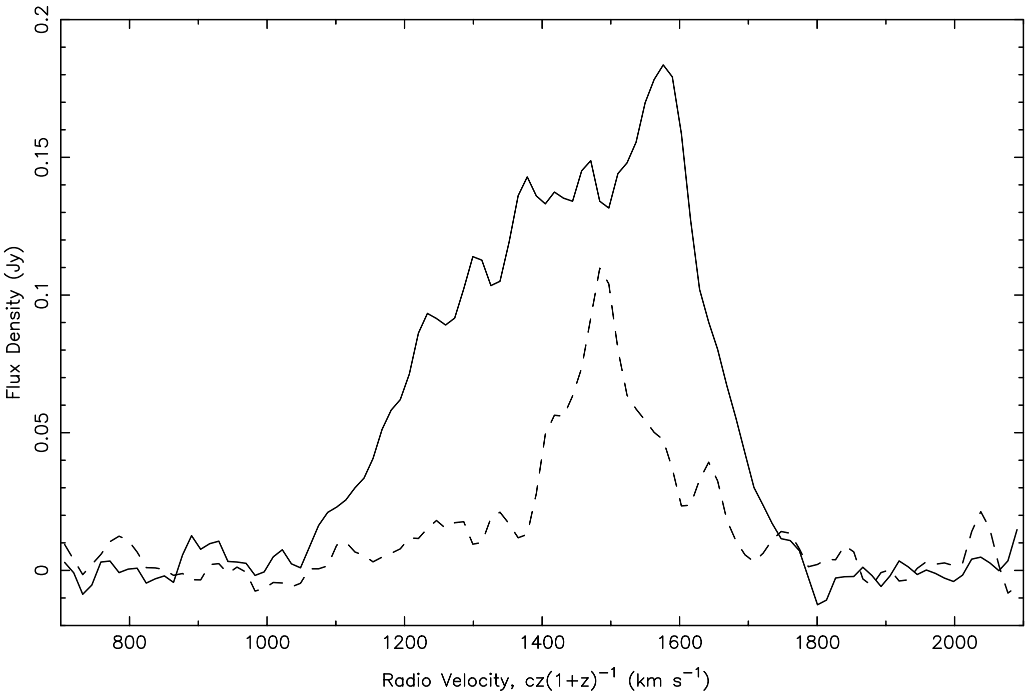

FIG. 3.—H I line profiles of NGC 2442 (*solid line*) and HIPASS J0731 − 69 (*dashed line*) from the HIPASS data. In each channel, the emission in a 28′ × 28′ box has been summed. Line profiles have been continuum-subtracted and then Hanning-smoothed.

file (also slightly asymmetric; Fig. 3) are a flux integral of 64 ± 4 Jy km s^{-1}, a heliocentric velocity of 1456 ± 40 km s^{-1}, and a full width at 20% of the peak intensity, $W_{20} = 550 \pm 12$ km s^{-1}.

The similarity in H I profile shapes raises the concern that HIPASS J0731 − 69 may just be a "ghost" of NGC 2442. We examined the five separate scans which pass through this region (each of which is displaced from the previous scan by 7′; Barnes et al. 2001) and found a firm detection in each one of them, confirming that HIPASS J0731 − 69 is not an artifact of either the scanning or the gridding process.

Of the 1000 or so brightest HIPASS sources examined by Koribalski et al. (2001), NGC 2442 was the only object found to have such a notable extension with no optical counterpart. Most other extended sources turn out to be associated with known loose groups of galaxies. At least two sizable H I clouds lying outside the zone of avoidance but apparently devoid of any stars have also been found by visual inspection of the HIPASS data (Kilborn et al. 2000; Koribalski 2001), but with velocities in the range 400–500 km s^{-1}, they are probably part of or just outside of the Local Group.

In an attempt to further characterize the nature of HIPASS J0731 − 69, we used the ATCA in its 750A configuration on UT 2000 August 25 to map the field of this emission. A mosaic of four pointings was observed over 10 hr, extending ~1° west and north of NGC 2442 and including NGC 2442 itself. These observations quite clearly show the H I in NGC 2442 but fail to detect any sign of HIPASS J0731 − 69 since the 3 σ column density achieved with the limited number of baselines and amount of time available (i.e., $\sim 10^{20}$ cm^{-2}) is still an order of magnitude greater than the peak column density found in the HIPASS data. We infer from this that the H I seen by HIPASS is indeed somewhat diffuse and not clumpy (on the arcminute scales, to which this ATCA configuration is most sensitive), as one might perhaps expect if it was associated with any particular optically visible galaxy.

There are no cataloged galaxies within a 15′ radius of the central position of HIPASS J0731 − 69 in the NASA/IPAC Extragalactic Database. We have examined the Digitized Sky Survey (DSS) for potential optical counterparts to the newly discovered gas. Although a total of seven independent objects were found within 15′ of the central position, none are more than 1′ in diameter, making it rather unlikely that any are new members of the NGC 2442 group (Garcia 1993). The most likely candidate object, an isolated spiral galaxy at $\alpha = 07^{\rm h}31^{\rm m}10^{\rm s}.4$, $\delta = -68°55'59''$ (J2000), has been found to have a redshift inconsistent with that of the NGC 2442 group (I. Perez 2000, private communication).

A channel map sequence (Fig. 4) shows that even with the large HIPASS beamwidth and coarse velocity resolution, HIPASS J0731 − 69 is resolved into multiple components. Two components, centered on $(\alpha, \delta) = (07^{\rm h}34^{\rm m}, -69°04')$ and $(07^{\rm h}31^{\rm m}, -69°20')$ (J2000), begin to appear at $V_\odot \sim 1325$ km s^{-1} and then grow separately before merging at a velocity near 1440 km s^{-1}. A Gaussian fit to this merged component yields a centroid of $\alpha = 07^{\rm h}31^{\rm m}39^{\rm s}.4$, $\delta = -69°01'36''$ (J2000). At velocities near 1340 km s^{-1} and 1380 km s^{-1}, there are the first signs of a direct connection of the emission from the northeast and the southwest components, respectively, to that from NGC 2442, and by 1418 km s^{-1}, both components are apparently joined with NGC 2442 as well as with each other. The merged component of HIPASS J0731 − 69 again appears well connected with NGC 2442 for most velocities in the range 1500–1600 km s^{-1}. However, it must be borne in mind that the separation of the two main components, as well as their distance from NGC 2442, are only 1–2 times the HIPASS

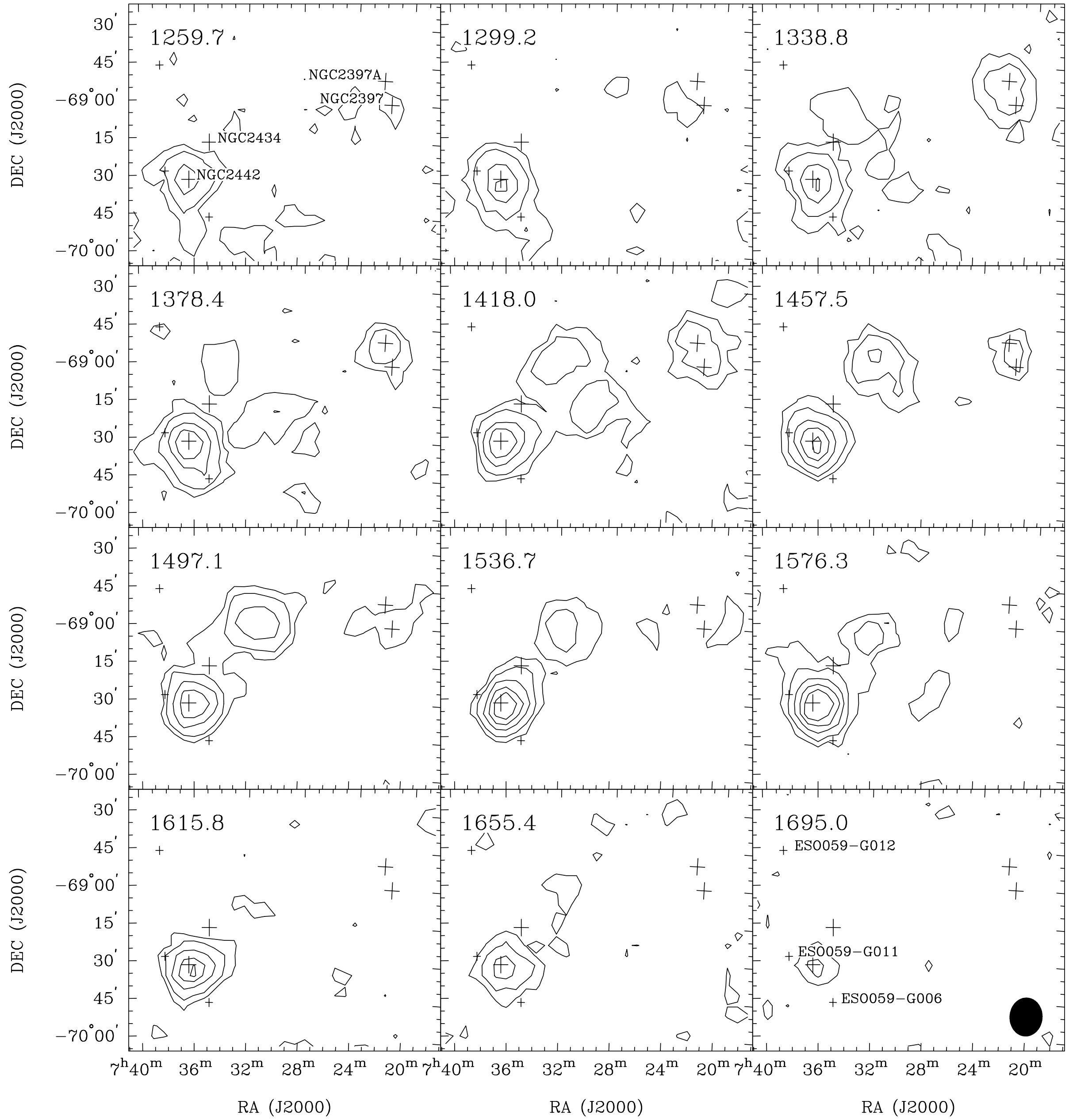

FIG. 4.—Channel maps of H I emission from the HIPASS observations of the region around NGC 2442. The contours correspond to flux densities of 15, 30, 60, 90, and 120 mJy beam^{-1}. For reference, the optical positions of the four major NGC galaxies in the field are marked in each panel with a large cross and identified in the first panel; three more ESO galaxies are marked with small crosses and identified in the last panel. HIPASS beam size is also indicated in the last panel.

beamwidth, so any apparent physical connections between each of them must be regarded with caution until higher resolution observations can be made.

3. DISCUSSION

Since the bulk of this new gas lies at a projected separation of nearly 40′ from NGC 2442 (and only slightly farther from NGC 2397), it is probably best characterized as an intergalactic cloud associated with the NGC 2442 group, although both its velocity range and Figure 1 suggest that the closest connection is to NGC 2442. One way to set limits on the actual separation of HIPASS J0731−69 from NGC 2442 would be to search for Hα emission from the cloud's surface that is due to ultraviolet photons escaping from the galaxy. Hα emission levels of 2–4 mR are expected for a cloud within 200 kpc of the galaxy (Bland-Hawthorn et al. 1998), and emission measures as low as 1 mR are now detectable with 4 m class telescopes (J. Bland-Hawthorn 2000, private communication).

Similar examples in nearby galaxy groups of intergalactic gas clouds without prominent optical counterparts include the Virgo cloud H I 1225+01 (Giovanelli & Haynes 1989), the Leo ring (Schneider et al. 1983), the H I cloud in the NGC 3256 group (English 1994), and the H I cloud superimposed on the blue compact dwarf FCC 35 in the Fornax Cluster (Putman et al. 1998a). Table 2 compares the global properties of these four systems with HIPASS J0731−69. In each of the first two cases, faint dwarf galaxies apparently associated with these gas clouds have since been identified (Chengalur, Giovanelli, & Haynes 1995; Schneider 1989). In

TABLE 2

Global Properties of Some Extragalactic H I Clouds

Source	$V_{\odot}$ (km s^{-1})	$\int S_{\rm H\,I} dV$ (Jy km s^{-1})	D (Mpc)	$M_{\rm H\,I}$ ($10^8\ M_{\odot}$)	Extent (kpc)	References
H I 1225+01	1275	42.4	20.0	40	200	1
Leo ring	700	70.9	10.0	17	260	2
NGC 3256 cloud	2868	15.0	37.0	48	110	3
FCC 35 cloud	1658	2.9	18.2	2.2	13	4
HIPASS J0731−69......	1481	18.0	15.5	10	180	5

References.—(1) Giovanelli & Haynes 1989; (2) Schneider 1989; (3) English 1994; (4) Putnam et al. 1998a; (5) this work.

the absence of either a contrast-enhanced photo or a deep CCD image of the area covered by HIPASS J0731−69, we cannot rule out the possibility of a Malin 1–like object (Bothun et al. 1987) with an extended low surface brightness disk and very compact bulge component. However, the failure to detect gas clumping with the ATCA makes it rather less likely that any optical (galactic) counterpart exists.

The complex velocity field of HIPASS J0731−69 illustrated by Figure 4 and the rather asymmetric H I profile of Figure 3 are inconsistent with a uniformly rotating disk structure. Rather, it is more likely that HIPASS J0731−69 is an extended streamlike feature of some kind. The H I velocity field for NGC 2442 of Houghton (1998) shows line-of-sight velocities ranging from just below 1100 km s^{-1} in the northeastern quadrant to over 1700 km s^{-1} in the southwest. However, it appears that gas in the northern arm with velocities in the approximate range of 1450–1600 km s^{-1} is being drawn out and away from the rest of the disk in an easterly direction toward the southwest component of HIPASS J0731−69. In addition, sections of the inner northern arm are displaced in velocity from the background disk by ~ 50 km s^{-1}. Both these distortions are consistent with gas being pulled out of the plane, and their respective velocities and alignments lead us to hypothesize that they may, with better sensitivity and resolution, prove to be contiguous with the various components of HIPASS J0731−69. Similar anomalous velocities and double line profiles in the northern arm were seen optically by Bajaja, Agüero, & Paolantonio (1999) and by Mihos & Bothun (1997).

HIPASS J0731−69 spans ~ 180 kpc and contains $10^9\ M_{\odot}$ of atomic hydrogen, making it comparable in scale to both the Virgo cloud and the Leo ring. The Leo ring contains as much gas as either of the nearby spiral galaxies M95 or M96, while the Magellanic System (LMC, SMC, Stream, Bridge, and Leading Arm) contains $\sim 10^9\ M_{\odot}$ of H I (Putman et al. 2001), or one-third as much gas as the Milky Way. The "forked" velocity structure of HIPASS J0731−69 is also not unlike that of the Magellanic Stream/Bridge/Leading Arm System (Putman et al. 1998b) or the sections of the Leo ring studied by Schneider (1985), which he was able to model quite well by a Keplerian orbit. The spatial resolution of the HIPASS data is insufficient to allow us to test any orbit models, but future mapping at higher resolution may enable the internal dynamics of this system to be understood.

Was the gas in HIPASS J0731−69 once part of NGC 2442? The H I mass-to–blue luminosity ratio for NGC 2442 alone [$\log (M_{\rm H\,I}/L_B) = -0.57$, using our H I mass and $B_T = 11.1$; Sérsic & Donzelli 1993] is identical to the median value for Sbc galaxies as a whole (Roberts & Haynes 1994). However, compared with other Sbc galaxies, NGC 2442 is slightly subluminous optically, and its H I content is also just below the median. Including HIPASS J0731−69 would then make the total atomic gas content of NGC 2442 about average for an Sbc galaxy (this of course assumes that the disturbance to NGC 2442 has not radically changed its apparent Hubble type). The scatter in each parameter exhibited by Sbc galaxies (~ 0.5 dex) means that global parameters are not particularly helpful in settling the question of the origin of HIPASS J0731−69.

We now briefly review how our discovery of HIPASS J0731−69 impacts the two main theories for the origin of the asymmetry in NGC 2442.

3.1. *Tidal Encounter?*

As mentioned in § 1, there are several candidate galaxies for a recent past interaction with NGC 2442. What kind of close encounter might have caused NGC 2442 to lose up to 25% of its own H I content (or strip an equivalent amount of gas from some other galaxy), while only mildly affecting its global kinematics, infrared luminosity, and star formation rate (Mihos & Bothun 1997)?

Large tidal tails and bridges on scales of 100 kpc or more are not uncommon in compact groups (e.g., the Leo triplet; Haynes, Giovanelli, & Roberts 1979) and in galactic mergers (see, e.g., the merger "sequence" imaged in H I by Hibbard & van Gorkom 1996). In such cases, however, there are usually two or more galaxies of comparable mass involved, with separations of this same order. In addition, there is growing evidence for the formation of "tidal dwarf galaxies" from the gas in these tails (Duc & Mirabel 1999). The resolution of the HIPASS data is not really adequate for us to determine whether HIPASS J0731−69 is an isolated cloud (or group of clouds) or if there is a bridge of material linking it directly to NGC 2442. We note that Houghton (1998), in her ATCA study of NGC 2442, observed a mild "stretching" of the H I disk toward the west but did not find any signs of an H I tail within the 34′ primary beam, making the former more likely.

Mihos & Bothun (1997) provide a model for a close passage of AM 0738−692 ~ 200 Myr ago, which appears to be reasonably successful at explaining many of the morphological peculiarities of NGC 2442. There is no specific prediction of a large gas cloud like HIPASS J0731−69 in this scenario (but then neither was there any particular reason to expect such a feature). According to this model, the northern arm in particular is not driven by a spiral density wave but is more like a tidal tail. Another good example of this phenomenon is the interacting pair NGC 6872/IC 4970 (Mihos, Bothun, & Richstone 1993), which, just as in NGC 2442, exhibits large velocity gradients across the width of the tidal arm as material originally drawn away from the disk begins to fall back in and is compressed and shocked.

This mechanism accounts quite naturally for the prominent dust lane, enhanced star formation, and unusual line profiles observed in the northern arm of NGC 2442. However, in the Mihos & Bothun (1997) model, it is hard to believe that such an innocuous object as AM 0738−692 could once have contained as much gas as is in HIPASS J0731−69 or that it could have removed such a large quantity of gas to such a large distance. If NGC 2442 has been the victim of a recent tidal encounter, then the existence of HIPASS J0731−69 makes it far more likely that the culprit is a more massive galaxy to the northwest, such as the elliptical galaxy NGC 2434 or perhaps even the spiral plus Magellanic irregular pairing of NGC 2397 and NGC 2397A.

3.2. *Ram-Pressure Stripping?*

The NGC 2442 system shares many of the characteristics of certain asymmetric galaxies that are suspected of being ram-pressure stripped of some of their H I as they pass through the intracluster medium. Among the best examples of this phenomenon are NGC 2276 (Gruendl et al. 1993), NGC 4273 (Davis et al. 1995), NGC 7421 (Ryder et al. 1997), and the Virgo Cluster galaxies NGC 4388 (Veilleux et al. 1999), NGC 4654 (Phookun & Mundy 1995), and NGC 4522 (Vollmer et al. 2000). The most distinctive features of these objects are (1) strongly asymmetric H I profiles; (2) a truncated optical and/or gas distribution on one side of the galaxy, often having a bow shock–like morphology; (3) a gaseous tail or "wake" in the opposite direction, possibly out of the disk plane; and (4) mild disturbance to an otherwise regular rotational velocity pattern. In some cases, the presence of a hot diffuse gas component is confirmed by X-ray satellite observations, but the intracluster medium is not always so obvious.

The deep optical image of NGC 2442 (Fig. 2) shows quite a sharp edge to the northern edge of the stellar disk when compared with the diffuse extensions to the southeast and southwest. The global asymmetry and sharp cutoff to the north side is even more pronounced in Hα (Ryder & Dopita 1993; Mihos & Bothun 1997). The northern arm may represent the bow shock, where the disk is ploughing into the densest part of the intergroup medium, resulting in the observed velocity jumps. Disk rotation would stretch out the shock front, with the leading edge at the eastern end of the northern arm and material flowing downstream along this arm to the west and south (this assumes the southern side of the disk of NGC 2442 is in the foreground). HIPASS J0731−69 would then represent a stream of gas trailing out behind (or completely detached from) NGC 2442, perhaps from a time when the galaxy experienced a particularly strong ram pressure. Both NGC 2442 and one of its companions to the south (ESO 059-G006) show distortions in their H I velocity fields (Houghton 1998), which could just as easily be due to their passage through some intergroup medium as to an interaction. However, a *ROSAT* HRI image barely detects NGC 2442 itself, let alone any hot diffuse gas.

It is interesting to contrast the global H I profile of NGC 2442 (Fig. 3) with the global ^{12}CO (1–0) profile of Bajaja et al. (1995); the asymmetry in the atomic gas distribution is *reversed* in the molecular gas distribution, with the bulk of the CO emission apparently coming from the northeast sector of the disk at lower velocities. Bajaja et al. (1995) did not survey the entire disk of NGC 2442 but were unable to detect ^{12}CO (1–0) much beyond the point where the northern arm bends back on itself. Since the molecular gas is predominantly located in the inner disk, where the total mass surface density is highest (and interstellar matter stripping least effective), any asymmetry in the CO distribution would tend to imply the action of tidal forces rather than ram pressure (Combes et al. 1988; Boselli et al. 1994). Since the ratio of molecular to atomic gas in NGC 2442 ($M_{\mathrm{H_2}}/M_{\mathrm{H\,I}} \sim 0.7$) is close to the average for Sbc galaxies (Young & Scoville 1991), this too slightly weakens the case for ram-pressure stripping.

Clearly, HIPASS J0731−69 is an important new clue in the puzzle of the disturbed appearance of NGC 2442 as well as being a significant object in its own right on account of its apparent rarity in the HIPASS survey. Follow-up observations with more compact configurations of the ATCA are planned, as well as higher spectral resolution observations with the Parkes multibeam system and will be crucial in telling us more about the origin of HIPASS J0731−69 and its relationship to NGC 2442.

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