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STARBURST-DRIVEN SUPERWINDS FROM INFRARED GALAXIES

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ABSTRACT

We present new data that indicate that strong far-infrared galaxies commonly have largescale emission-line nebulae whose properties are suggestive of mass outflows ("superwinds"), presumably driven by the high supernova rate associated with the central starburst. These data include longslit spectra of M82 which show that the radial variation of the gas pressure in the emission-line nebula is in excellent agreement with the Chevalier and Clegg (1985) wind model. The M82 nebula also has a LINER spectrum, consistent with shock-heating. We find morphologically and spectroscopically similar emission-line nebulae in NGC253 (associated with the diffuse X-ray gas along the galaxy minor axis), and in Arp220 and NGC6240 (where the nebulae are tens of kpc in size). We have also conducted a longslit spectroscopic investigation of 20 additional very powerful (~ 10E12 L(sun)) far-infrared galaxies and find that they generally have spatially-extended emission-line nebulae whose spectra closely resemble that of the M82 nebula. If the "superwind" interpretation is correct, it could have many important consequences in extragalactic astronomy.

1. INTRODUCTION

The discovery of a class of galaxies with far-infrared luminosities of 10E11 to 10E12 L(sun) - 10 to 100 times larger than the corresponding optical luminosities - is probably the most significant extragalactic discovery made by IRAS. While these far-infrared galaxies ("FIRG's") are the subject of intense scientific scrutiny, the most fundamental questions are not yet answered: What powers the strong far-infrared emission? How are the observed optical emission-lines and nonthermal radio continuum emission related to the infrared power-source? What is the impact of the prodigious release of energy on the surrounding galaxy? The answers to these questions are likely to prove of considerable value to our quest to understand star formation, galaxy formation and evolution, and the nature of nuclear activity in galaxies.

In order to address these questions, we have embarked on two related investigations of FIRG's. The first is a detailed study of the physical state, kinematics, and morphology of the emission-line nebulae associated with the nearest FIRG's. The second is a systematic spectroscopic and direct imaging survey of a moderately large sample of optically faint IRAS galaxies with very powerful infrared emission. As we will discuss below, the data we have collected so far strongly suggest that FIRG's are commonly associated with largescale mass outflows ("superwinds") of the kind hypothesized by Chevalier and Clegg (1985-hereafter CC). Further details concerning our data and their interpretation can be found in Heckman, Armus, and Miley (1986) and McCarthy, Heckman, and van Breugel (1986).

2. THE MODEL

We begin by briefly summarizing the model that will serve as the interpretational framework for the data we will present and review in section 3. This model was originally proposed by CC to account for the X-ray and emission-line nebula associated with the prototypical FIRG, M82.

The starburst underway in the circumnuclear (100 to 1000 pc-scale) molecular disk of M82 implies a high supernova rate. CC hypothesize that the kinetic energy of the supernova ejecta is efficiently thermalized as remnants intersect one another at high velocities, producing a central cavity of hot gas which then expands outward in the form of a fast (several*10E3 km/sec) wind. While the CC model is for a spherically-symmetric wind, both the data (see below) and physical intuition suggest that a bipolar wind will be produced as the hot gas preferentially escapes along the rotation axis of the circumnuclear disk. In the CC model the wind material itself is a negligible source of radiation. The nebula in M82 is instead produced by shock-heated clouds that have been entrained in the wind.

3. THE DATA

3.1. M82

As the nearest and best-studied FIRG, M82 is the "Rosetta Stone" for the wind model described above. We will therefore summarize all the relevant observational evidence, including the new results from our long-slit spectroscopic investigation.

First, as emphasized by CC, both the starburst models of Rieke et al. (1980) and the population of compact time-variable radio sources observed by Kronberg et al. (1985) imply that supernovae are occuring in M82 at the rate of one every several years.

Second, recent high-resolution CO maps of M82 (e.g. Nakai 1984) show clear evidence for a central cavity in the circumnuclear molecular disk (the "nozzle" for the wind). The molecular annulus is coincident with the region of intense infrared and radio emission, and is apparently coplanar with the largescale stellar disk of M82.

Third, both the well-known emission-line nebula and the cospatial X-ray nebula (Watson et al. 1984) are oriented perpendicular to the molecular annulus (they lie along the galaxy's minor axis).

Fourth, the kinematics of the emission-line gas in the M82 nebula are strongly suggestive of high-speed outflow (Axon and Taylor 1978; J. Bland and R.B. Tully, private communication).

Fifth, our new spectroscopy shows that the pressure in the emission-line nebula falls smoothly and monotonically with radius (see Fig. 1). The form of P(r) is in excellent agreement with the predictions of the CC model. Moreover, the pressures in the emission-line gas agree with those estimated in the X-ray gas. We note that this directly observed radial variation in gas pressure rules out models in which most of the optical line-emission in M82 is dust-scattered nuclear light.

Finally, our new data also demonstrate that the M82 nebula has a LINER spectrum, very similar to the emission-line spectra of gas heated by shocks (e.g. old supernova remnants - see Table I).

Thus, the available data on M82 provide evidence for the supernovae to drive the wind, for the nozzle to channel the wind, and for the shock-heated material which traces the wind's passage and probes its physical properties.

Table I
Emission-Line Ratios in Far-Infrared Galaxies

(1) Name	(2) [OIII]/Hβ	(3) [OI]/Hα	(4) [NII]/Hα	(5) [SII]/Hα
SNR's	0.0 to 0.6	-1.1 to -0.3	-0.5 to 0.1	-0.4 to 0.2
Shock Model	0.2	-1.1	-0.2	-0.2
M82 Nebula	-0.1	-1.1	-0.4	-0.4
NGC253	-0.5	?	0.0	-0.3
Arp220	0.2	-0.7	0.0	-0.2
NGC6240	0.2	-0.6	0.0	-0.1
FIRG Sample	-0.2 to 0.6	-1.5 to -0.5	-0.5 to 0.1	-0.6 to 0.0

Notes to Table I.

Col. 1) Supernova remnants (SNR's) from Dopita et al. (1984) and references therein. The Shock Model line ratios are the average of models B and C in Raymond (1979) and models D and E in Shull and McKee (1979). The FIRG Sample is described in section 3.4 in the text.
Cols. 2-5) The logarthmic ratios of the fluxes of the [OIII]λ5007 and Hβ; [OI]λ6300 and Hα; [NII]λ6583 and Hα; [SII]λ6717+6731 and Hα lines.

3.2 NGC253

NGC253 is nearly a perfect match to M82 in both its distance and far-infrared luminosity. As such, it provides an important test of the generality of the phenomena discussed above. Like M82, NGC253 has i) a central circumnuclear molecular disk which is coincident with the region of intense infrared and radio emission (Scoville et al. 1985; Turner and Ho 1983), ii) an X-ray nebula extending along the galaxy minor axis (Fabbiano and Trinchieri 1984), and iii) a region of high-velocity outflow seen in the optical emission-line gas (e.g. Ulrich 1978).

Our new data considerably strengthen the resemblance between NGC253 and

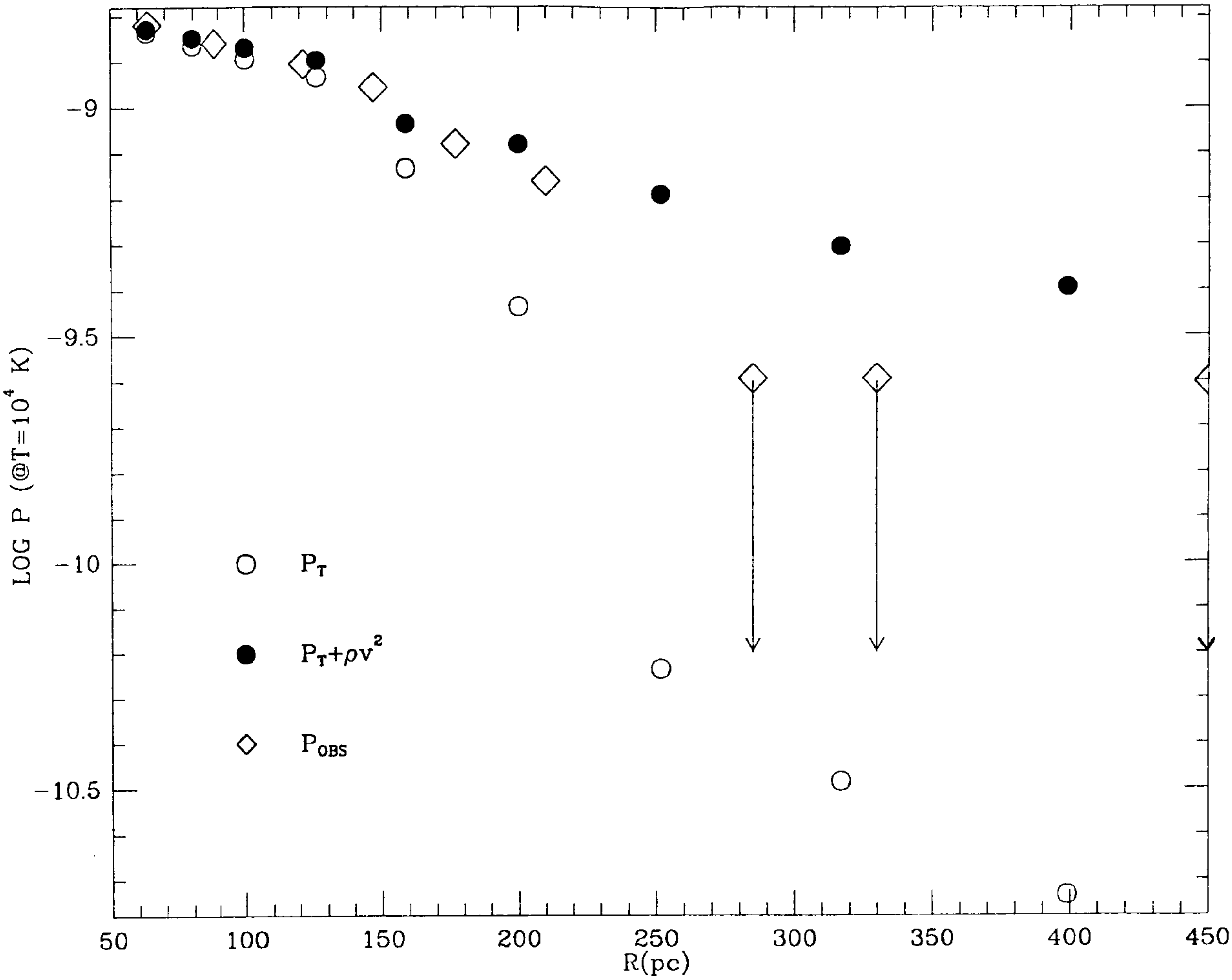

Figure 1. The observed radial dependence of the gas pressure in the M82 nebula (=2nkT, where n is the electron density as measured by the red [SII] lines and T is taken to be 10,000K) is plotted along with the predicted thermal and total (ram plus thermal) pressures in the wind model calculations of Chevalier and Clegg (1985). A best fit between the model and the data is achieved if the pressures are a factor of 5 below the maximum values allowed by the model (as shown).

M82. A narrowband (H-alpha) image shows that there is a striking morphological relationship between the optical and X-ray emitting gas along the minor axis, as in M82 (see McCarthy, Heckman, and van Breugel 1986). Moreover (again as in M82), this gas has a LINER spectrum, suggestive of shock-heating (Table I).

3.3 Arp220 and NGC6240

These galaxies are two of the closest examples of the class of very-powerful FIRG´s, having luminosities one to two orders-of-magnitude larger than M82 or NGC253. Rieke et al. (1985) have recently shown that many of their properties can be explained by a scaled-up version of the starburst models they had successfully applied to M82 and NGC253.

Our new narrowband (H-alpha) images and longslit spectra suggest that superwinds are also occurring in these two FIRG´s. Large (tens of kpc) and morphologically spectacular emission-line nebulae are present in both galaxies (see Figs. 2 and 3). The Arp220 nebula is strongly bipolar in appearance, consisting of a bright central "jet" and faint outer "bubbles". The inner feature is oriented roughly perpendicular to the central dust-lane in Arp220. The NGC6240 nebula is more complex, with a bright central "starfish" elongated along the galaxy´s minor axis, and an outer region of filaments and arcs.

Both nebulae have classic LINER spectra, at least in the bright inner "jet" and "starfish" (Table I). They are thus similar to the M82 and NGC253 nebulae both spectroscopically and morphologically. Little is yet known concerning the kinematics of the gas in Arp220 and NGC6240, however high velocity (several hundreds of km/sec) noncircular gas motions are clearly present in both galaxies (see Table 2 in Heckman et al. 1986 and related discussion).

3.4 A Survey of Very Powerful FIRG´s

We have recently undertaken a spectroscopic and multi-color direct imaging survey of a sample of optically-faint IRAS sources chosen to have the same far-infrared spectral-energy-distribution as Arp220 and NGC6240. Our principle results of special relevance to the present discussion are as follows:

First, most of the 20 galaxies observed spectroscopically resemble the M82 nebula (see Table I). About half can be comfortably classifed as LINER´s, while most of the rest have spectra that are intermediate between a LINER and an HII region.

Second, the emission-line regions are often spatially resolved, and several nebulae are larger than 10 kpc in size. We have just begun a narrowband imaging program to determine the statistical properties of these nebulae.

Third, as is apparently the case for FIRG´s in general, the galaxies are generally very disturbed in their optical morphology, suggesting that galaxy collisions/mergers are important in the FIRG phenomenon.

4. IMPLICATIONS

The evidence summarized above implies that the CC model for largescale

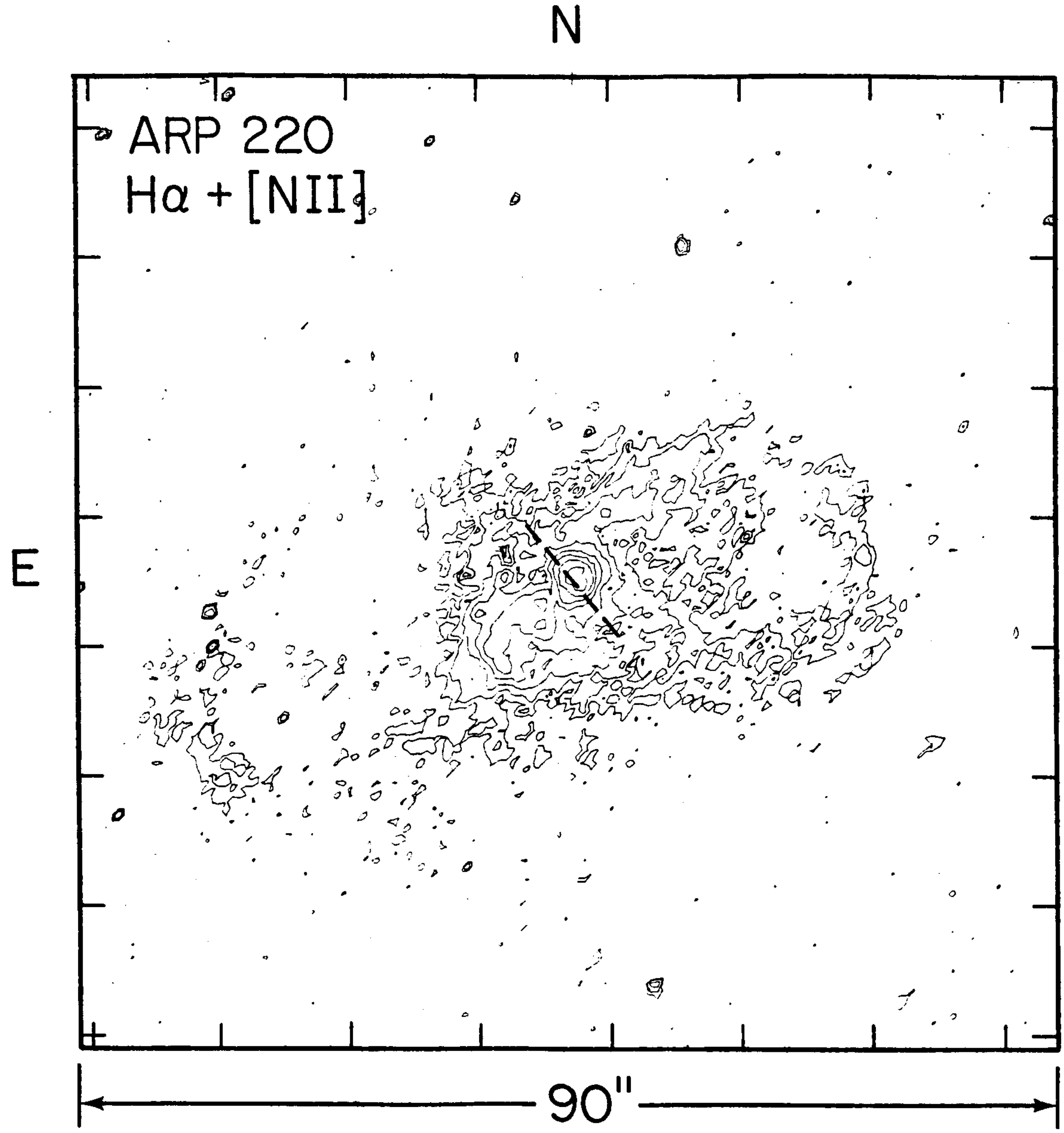

Figure 2. Contour plot of a continuum-subtracted H-Alpha image of Arp220. The first contour is at a surface brightness of 3.4E-17 ergs/(cm**2 sec arcsec**2) and each subsequent contour is at a factor 2 higher brightness. The dashed diagonal line represents the orientation of the central dust lane in Arp220.

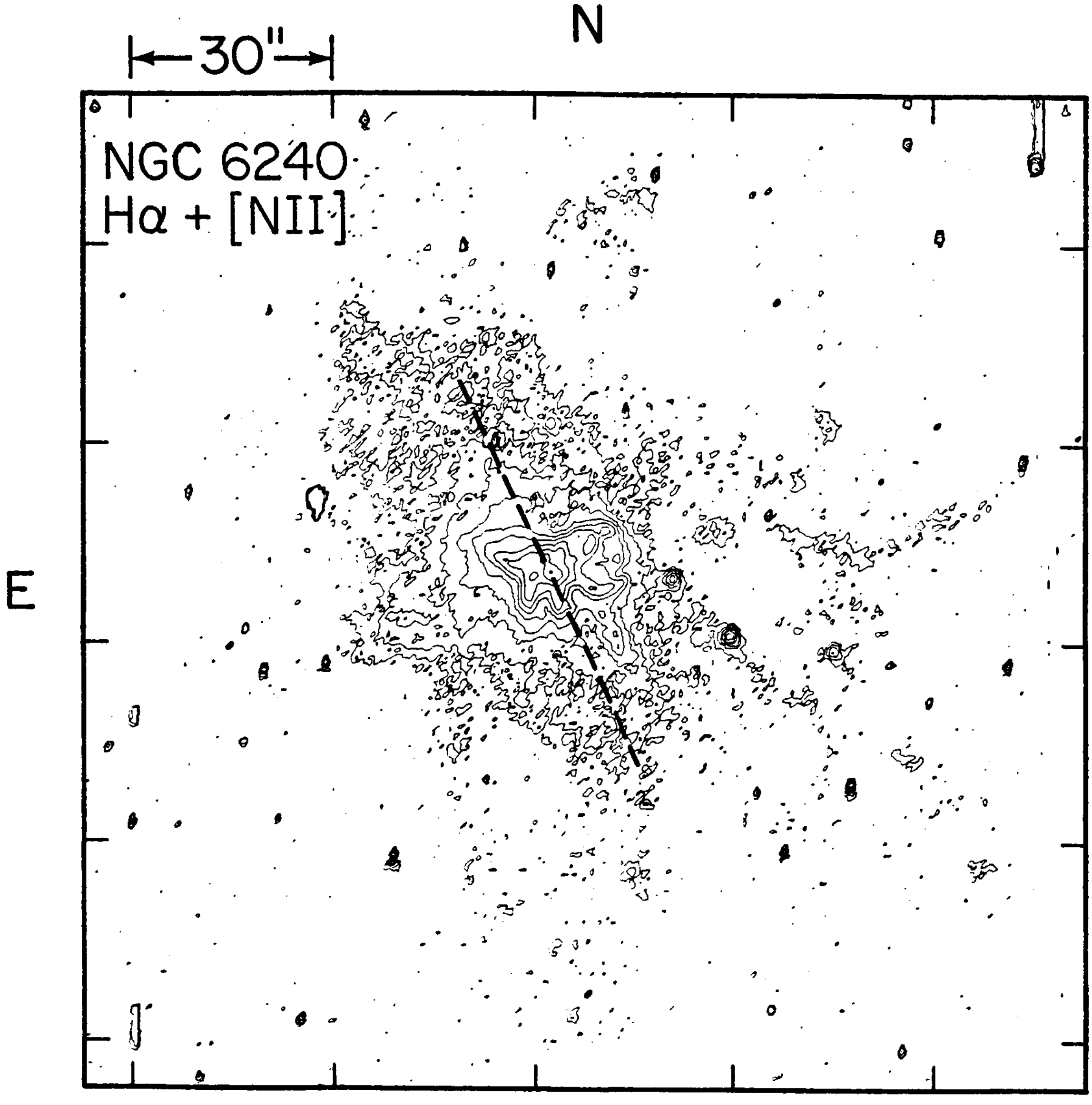

Figure 3. Contour plot of a continuum-subtracted H-Alpha image of NGC6240. The first contour is at a surface brightness of 6.6E-17 ergs/(cm**2 sec arcsec**2) and each subsequent contour is at a factor 2 higher brightness. The dashed diagonal line represents the orientation of the major axis of NGC6240.

mass outflows (superwinds) driven by circumnuclear starbursts may have general applicability to powerful far-infrared galaxies. If so, this will have many far-reaching implications.

Simply scaling the CC wind parameters for M82 by the far-infrared luminosity would mean that the superwinds in galaxies like NGC6240 and Arp220 have mass fluxes of 10 to 100 M(sun)/year of highly enriched material and kinetic energy fluxes of 10E44 to 10E45 ergs/sec. If, as suggested by the models of Rieke et al. (1980, 1985), starbursts last for about 10E8 years, then these galaxies will inject 10E9 to 10E10 M(sun) and 10E60 ergs into the intergalactic medium.

The consequences of the superwind model (if it is correct) may be profound for our understanding of galaxy formation, the chemical and thermal evolution of the intergalactic and interstellar media, the nature of QSO absorption-line clouds, and many related topics. The main need at present is to place the model on a more secure observational footing by combining detailed investigations of the nearest examples of possible superwinds with continued survey work on a large sample of FIRG's. Such work is underway.

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DISCUSSION

WINDHORST:

I assume that the shock heated gas implied by your model would produce a fairly hard x-ray spectrum. Would not these star forming galaxies make up for the rest of the hard x-ray background, or even exceed it?

HECKMAN:

The x-ray spectrum need not be very hard, since the x-rays are produced by clouds that are shock-heated by the wind. These clouds will be heated to only modest temperatures ($T \lesssim 10^7$ K) if they are relatively dense.