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ENERGETIC OUTFLOWS IN LUMINOUS INFRARED GALAXIES

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RESUMEN

Hemos obtenido observaciones Fabry-Perot de gran campo de las galaxias con brote de formación estelar M82 y NGC 253, en varias líneas intensas de emisión (Hα, [NII]λ6583, [OIII]λ5007, Hβ). Estos extraordinarios datos revelan que los filamentos ópticos sobre el eje menor, supuestamente asociados con "vientos galácticos" son altamente energéticos ($\sim 10^{55}$ ergs) y muestran un comportamiento complejo. Hemos también obtenido imágenes profundas en B, R, I, y Hα de M82, para examinar con más cuidado los detalles espaciales de la estructura filamentaria. Estos datos suministran tanto información cinemática detallada y diagnósticos de las líneas de emisión para modelar el flujo emergente.

ABSTRACT

We have obtained wide-field Fabry-Perot observations of the starburst galaxies M82 and NGC 253 in several strong emission lines (Hα, [NII]λ6583, [OIII]λ5007, Hβ). These remarkable data reveal that the minor axis optical filaments, presumably associated with "galactic winds", are highly energetic ($\sim 10^{55}$ ergs) and display complex behavior. We have also obtained deep B, R, I, and Hα imagery of M82, in order to more carefully examine spatial details of the filamentary structure. These data provide both detailed kinematic information and emission-line diagnostics for modeling the outflow.

Key words: **GALAXIES: INDIVIDUAL (M82, NGC 253) — GALAXIES: KINEMATICS AND DYNAMICS — GALAXIES: STARBURST**

1. INTRODUCTION

In recent years, it has become clear that studies of so-called "starburst" galaxies may provide fundamental insights into the mechanism by which stars form. This knowledge precedes even a rudimentary understanding of galaxy formation and evolution. The key issues to be resolved include: What determines the form of the initial mass function? What environmental properties control the rate and efficiency of star formation? Are starbursts indicative of a higher *rate* or a higher *efficiency* in forming stars?

Our recent Fabry-Perot and optical observations permit us to approach the general problem of starburst galaxies through study of a specific phenomenon, that of the nuclear outflows in two of the closest and most spectacular starburst galaxies, M82 and NGC 253 (Heckman, Armus, & Miley 1990). The high supernova rates in the central cores of both galaxies (0.1–0.3 yr^{-1}) are expected to heat gas to temperatures greatly in excess of the galactic virial temperature. Several authors have produced detailed models of the resulting outflows (Chevalier & Clegg 1985; Mathews & Doane 1993). An excellent review of recent work can be found in Heckman, Lehnert, and Armus (1993).

2. OBSERVATIONS

Despite theoretical predictions, galactic winds have eluded detection in ordinary galaxies at any wavelength (Bregman 1978). Indirect evidence was provided by Einstein observations of the starburst systems M82

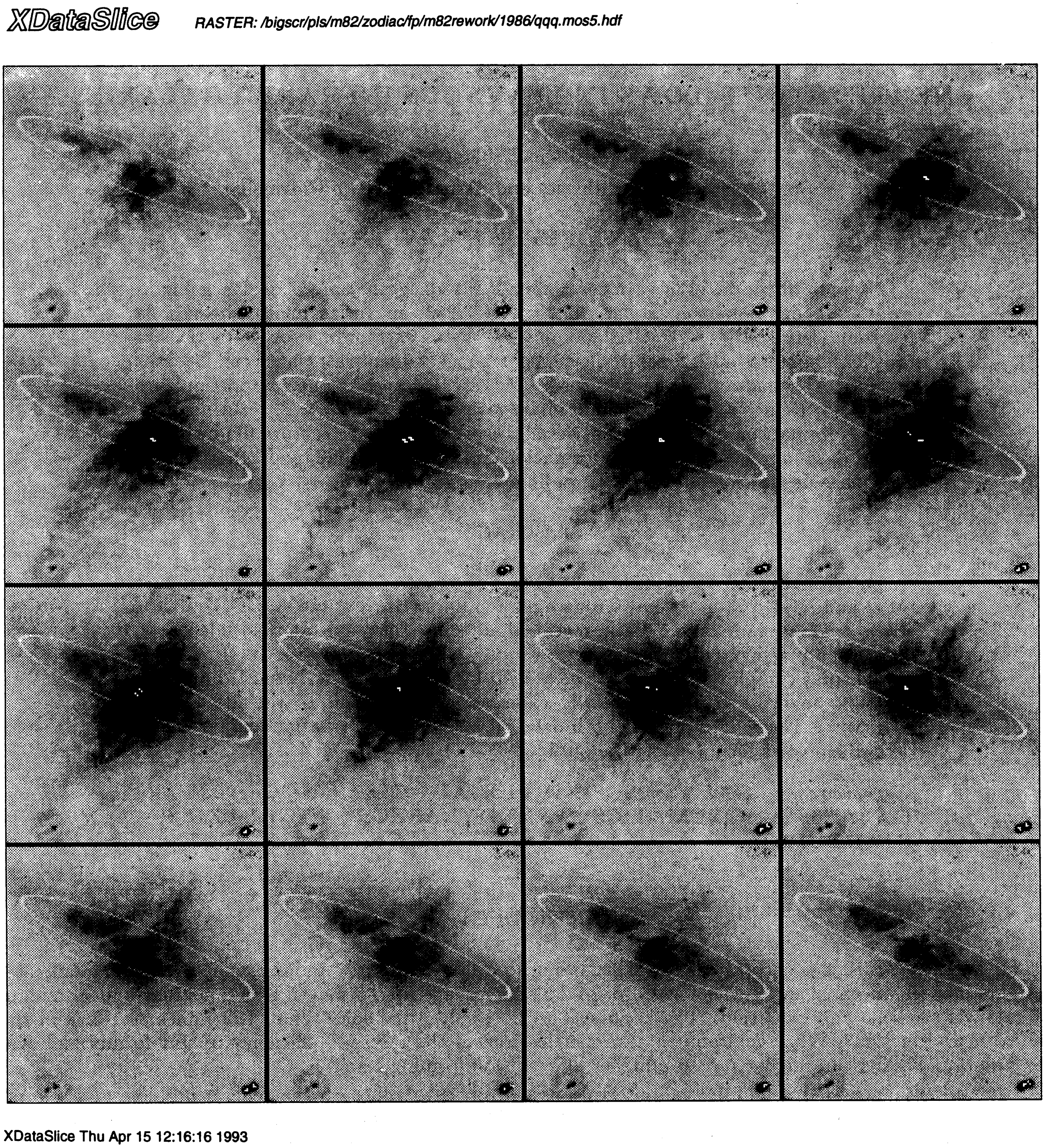

Fig. 1.— A sequence of 16 monochromatic images of M82 spanning the Hα line over a total velocity range of 800 km s^{-1}. The field of view is 215″ square in increments of 0.86″ pix^{-1}. The position angle of the edge-on galactic disk lies almost NE–SW. Along the minor axis, the large-scale bipolar wind is clearly evident as blueshifted emission to the SE and redshifted emission to the NW. The complete Fabry-Perot data set provides photometric and kinematic information at more than 60,000 pixel positions for each of the Hβ, [OIII]λ5007, Hα, and [NII]λ6583 emission lines.

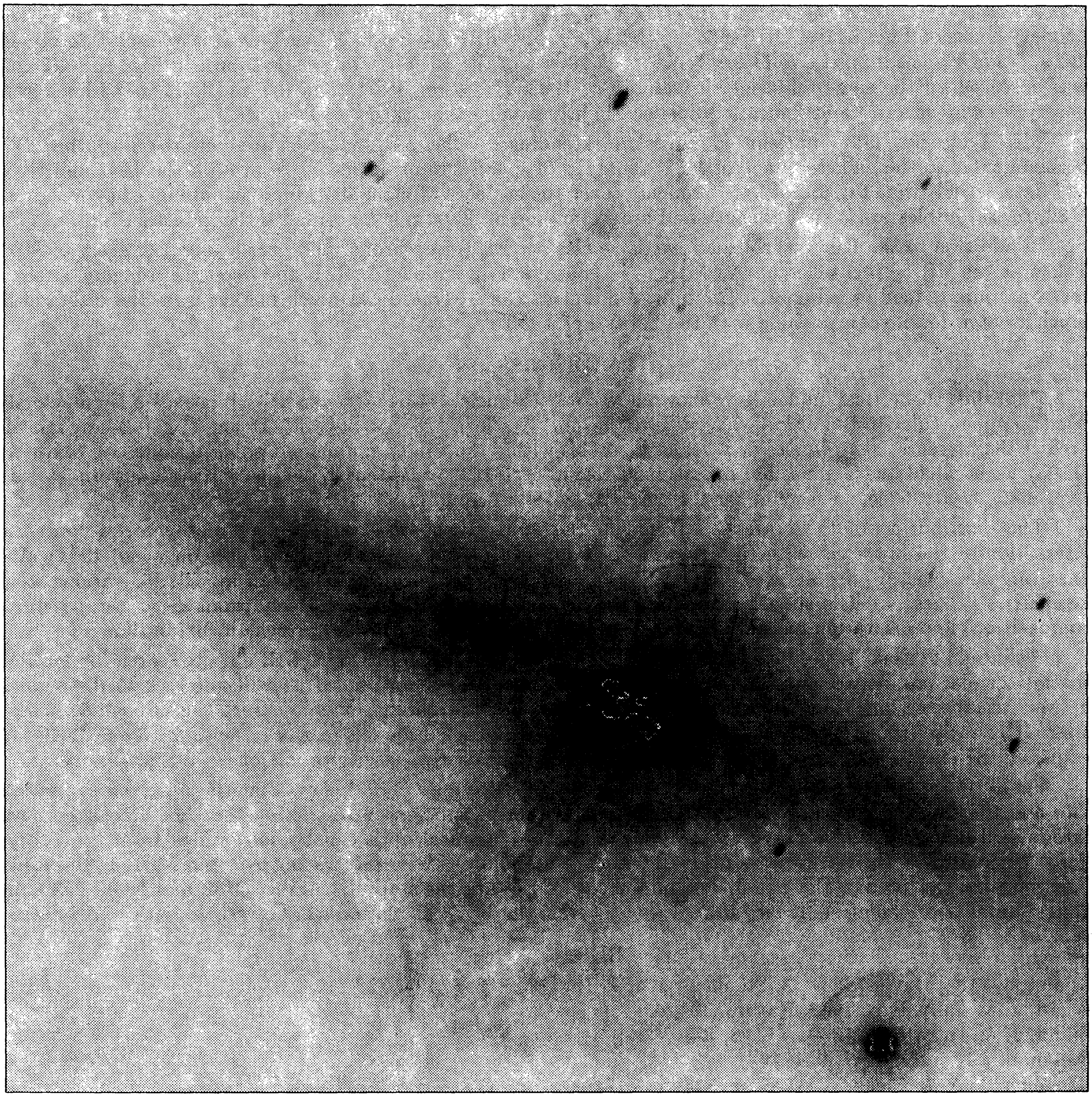

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Fig. 2.— A deep image of M82 in the light of Hα, consisting of five stacked images of 600 seconds duration each. The field of view is 432″ square in increments of 0.70″ pix^{-1}. The depth of the image reveals an immensely complex arrangement of filaments within the minor-axis outflow. Spatial comparisons of this image with high resolution X-ray maps allow one to distinguish between several possible sources for the X-rays (i.e., shocks, hot wind bremsstrahlung).

(Kronberg *et al.* 1985) and NGC 253 (Fabbiano & Trinchieri 1984), which show extended soft X-ray emission along their minor axes. Direct confirmation of these winds in the optical is provided by our Fabry-Perot observations of both galaxies. As outlined in Bland and Tully (1988), M82 was observed at the CFH 3.6 meter telescope in 1986, using the Hawaii Imaging Fabry-Perot Interferometer (HIFI; Bland & Tully 1989). The primary emission lines of Hα, [NII]λ6583, [OIII]λ5007, and Hβ were observed with a velocity resolution of $\sim$65 km s^{-1} and a spatial pixel size of 0.86$''$ pix^{-1}. A subset of the Hα observations is shown in Fig. 1. NGC 253 was observed on the same telescope in October of 1992, also using HIFI. The Hα and [NII]λ6583 lines were observed using spectral and spatial resolutions slightly smaller than those used for M82.

Fig. 1 clearly shows blueshifted emission extending to the SE and redshifted emission to the NW, perpendicular to the galactic plane of M82. Analysis of spectrograms extracted from both the M82 and NGC 253 data reveals that the minor axis filaments cover the surfaces of elongated, bipolar bubbles. In the case of M82, these bubbles are 2 kpc in length and are expanding at 600 km s^{-1} normal to the galactic disk.

In addition to the Fabry-Perot data, we have also acquired deep broad- and narrow-band imagery of M82. Taken at the UH 88 inch telescope in March of 1989, the data include B, R, I, and deep Hα imagery across a seven arcminute field (see Fig. 2). The optical filaments can be traced out much further from the disk and in much greater detail than possible with the Fabry-Perot data.

3. DISCUSSION

Published theoretical models have shown how compact nuclear starbursts can drive large-scale, high-velocity winds perpendicular to the disk of the galaxy (Chevalier & Clegg 1985; Mathews & Doane 1993). These models predict the pressure, density, and flow velocity profiles within the wind. In a related paper, Doane and Mathews (1993) have calculated a plausible initial mass function (IMF), consistent with the observed supernova rate (Kronberg *et al.* 1985), to account for the observed outflow energies.

The distribution of the optical filaments in the Fabry-Perot observations presumably arises from the interaction of the hot wind with the external medium seen at radio wavelengths (Appleton *et al.* 1981). We are using the general purpose code CLOUDY (Ferland 1990) to calculate ionization models for various wind geometries. These models should ultimately provide insight into the plasma conditions (e.g., temperature, composition) and excitation mechanisms (e.g., shocks, X-ray photoionization) present in the outflow.

We intend to make use of high resolution (4$''$) archival Einstein and ROSAT HRI data to search for detailed spatial correlations between the X-ray emission and the optical filaments. This will allow us to distinguish between X-rays arising from the post-shock region and bremsstrahlung emission from the hot wind. These alternatives arise from opposite energetic extremes in the published models (e.g., Mathews & Doane 1993). In addition, the extended X-ray emission will help constrain the energy density profile of our outflow models.

Finally, the stellar evolutionary models of Doane and Mathews (1993) show that the observed supernova rate and the total dynamical mass are the most important parameters in restricting the IMF. The supernova rate is well determined (Kronberg *et al.* 1985), and the dynamical mass can be determined from the Fabry-Perot kinematics at the turnover radius ($\sim$100 km s^{-1} at 350 pc). After integrating over the derived luminosity function, one can predict the bolometric luminosity of the nuclear starburst. Since M82 and NGC 253 emit almost all of their radiation at far infrared wavelengths, the IMF calculation can be verified with IRAS data.

REFERENCES

Appleton, P.N., Davies, R.D., & Stephenson, R.J. 1981, MNRAS, 195, 327

Bland, J. & Tully, R.B. 1988, Nature, 334, 43

Bland, J. & Tully, R.B. 1989, AJ, 98, 723

Bregman, J.N. 1978, ApJ, 224, 768

Chevalier, R.A. & Clegg, A.W. 1985, Nature, 317, 44

Doane, J.S. & Mathews, W.G. 1993, ApJ, in press

Fabbiano, G. & Trinchieri, G., 1984, ApJ, 286, 491

Ferland, G.J. 1990, *Hazy (Cloudy 76.03) Manual*

Heckman, T.M., Armus, L., & Miley, G.K. 1990, ApJS, 74, 833

Heckman, T.M., Lehnert, M.D., & Armus, L. 1993, in *Evolution of Galaxies and Their Environments*, eds. H. Thronson and M. Shull, (Kluwer), in press

Kronberg, P.P., Biermann, P., & Schwab, F.R. 1985, ApJ, 291, 693

Mathews, W.G. & Doane, J.S. 1993, ApJ, in press

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