Far-Infrared Polarization of Galaxies with SOFIA

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Jones, T. et al. (in preparation) and Lopez-Rodriguez et al. (in preparation)

Near- to mid-infrared (NIR, MIR; 1-13 µm) total and polarized flux observations from the ground have been key to advance our understanding about the emission and distribution of dust in galaxies as well as the morphology of their magnetic fields. However, the atmosphere is opaque to the 50-220 µm range and observations are impossible from ground-based telescopes. Furthermore, polarimetric capabilities have been very limited in this wavelength range. HAWC+ has opened a new window to explore active galactic nuclei (AGN) and starburst galaxies, providing the best angular resolution within the 40-300 µm range of the current suite of instruments. We here present the results of a massive spiral galaxy containing an AGN, NGC 1068, and a starburst galaxy, M82, observed at 53 um and 89 um with the far-IR (FIR) polarimeter HAWC+ onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). Specifically, our polarization observations of NGC 1068 at 89 µm have shown for the first time a magnetized arm along the spiral inner arms of the galaxy. Our polarized flux observations of M82, in combination with previously published NIR polarimetric observations, have shown evidences of a galactic magnetic wind at scales of several hundred parsecs.

Magnetic Fields in Galaxies

Over the past few decades astronomers have detected the presence of magnetic fields in galaxies at all range of scales, finding them to be ubiquitous on extragalactic sources. These major studies have been performed using optical and radio observations (for a review see Krongerg 1994, Beck 2015). Specifically, magnetic field properties have been inferred through the polarization from extinguished light in the interstellar medium (ISM), and Faraday rotation by synchrotron emission. Polarized extinction traces ordered fields (Scarrott et al. 1991), while synchrotron unpolarized emission traces turbulent fields (Fletcher et al. 2011). Magnetic fields provide additional pressure to the ISM and intergalactic gas, couple cosmic rays to the non-relativistic gas, and in specific ratios between the magnetic pressure to the dynamical and thermal energy of the gas, can dominate the galaxy dynamics. Magnetic fields are important dynamically as they affect the gas flows and drive the inflows/outflows of gas.

M82: A Starburst Galaxy

M82, from an infrared perspective, is the archetypical starburst galaxy (e.g. Telesco 1988, Telesco et al. 1989) with an infrared luminosity of 3 x $10^{10} L_\odot$ and a star formation rate estimated at 13$M_\odot$ yr^{-1}. M82 has a bipolar superwind emanating from the central region, stretching well into the outer halo area (e.g. Shopbell & Bland-Hawthorn 1998, Ohyama et al. 2002). The geometry of the magnetic field in the central starburst and in the galactic wind can be investigated using a number of different techniques. Classic interstellar polarization (in extinction) at 1.65 µm in the Near-Infrared (NIR) by Jones et al. (2000) showed evidence for a near vertical field geometry at the nucleus (Fig. 1). However, optical and NIR polarimetry is strongly contaminated by scattering of light from the very luminous nucleus of M82, and this was clearly evident in the NIR polarimetry.

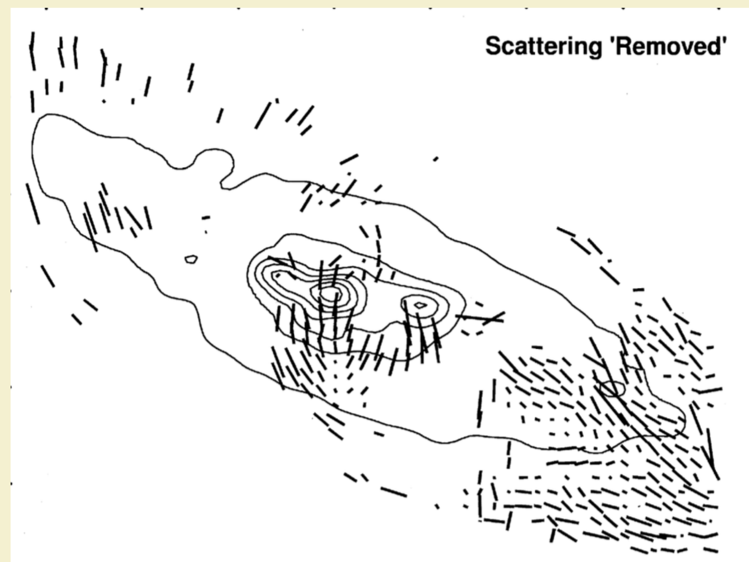
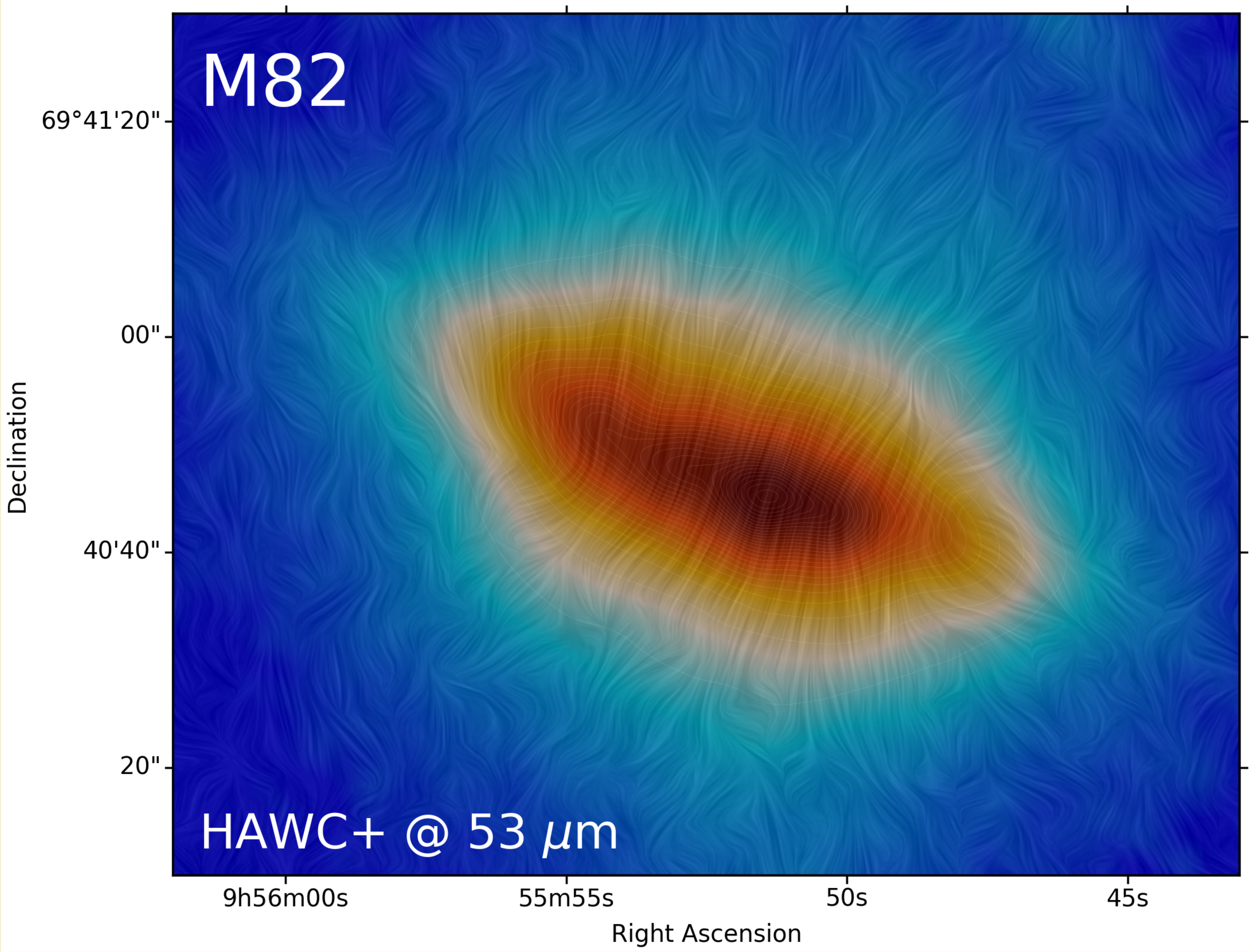


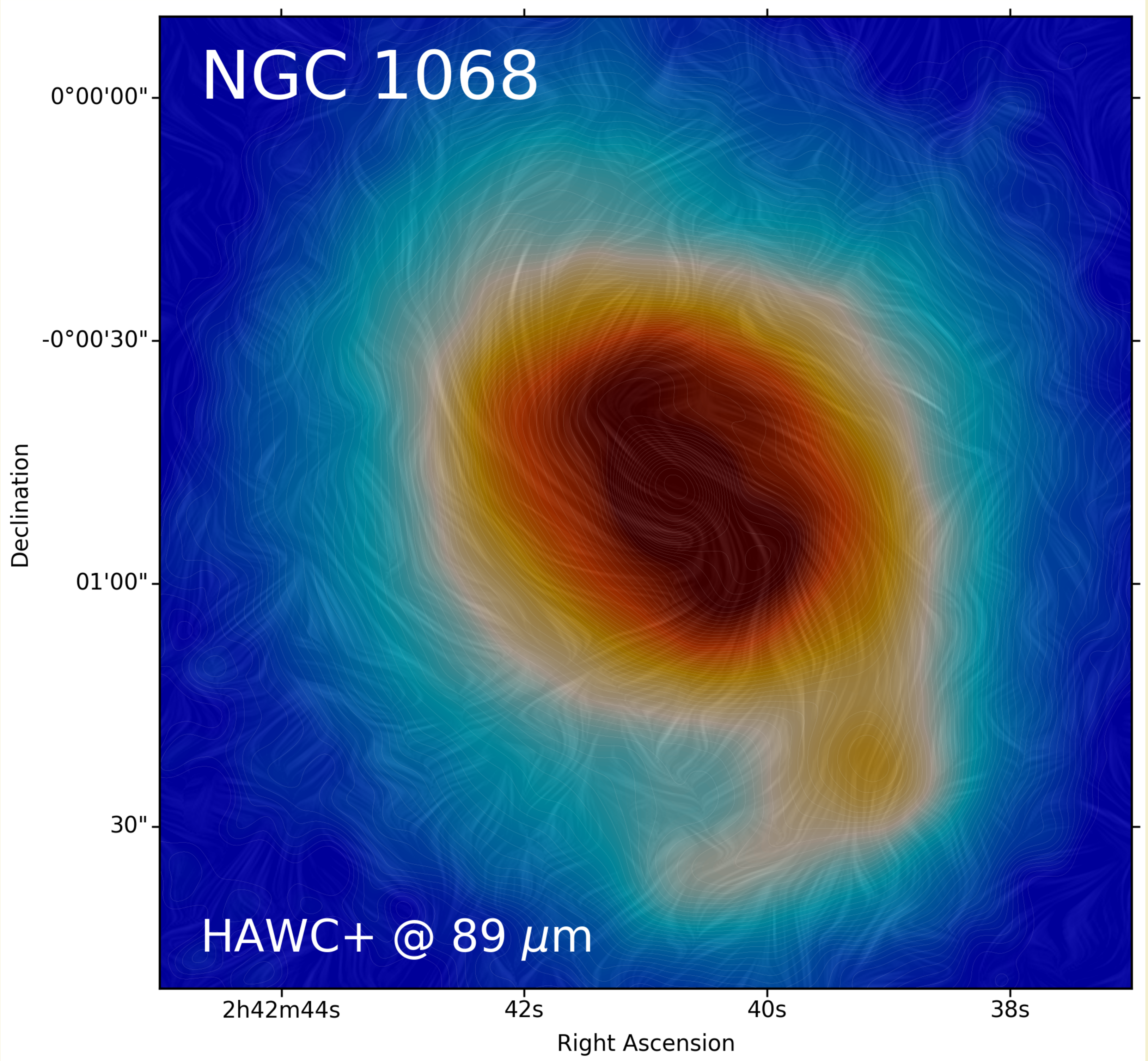
Figure 1: NIR polarization of M82 showing only the polarization vectors dominated by dichroic absorption (Jones et al. 2000). Note the similarity of these vectors with those observed by HAWC+, which indicates that a polar wind dominates the nuclear polarization at IR wavelengths.



M82: Total flux (color scale) with the inferred magnetic field (LIC map) using HAWC+ observations.

NGC 1068: A Spiral and Active Galaxy

Radio synchrotron observations of galaxies have been extensively used to study the relationship between the spiral arms and the magnetic field geometry in disk systems (see Beck & Wielebinski (2013) for a review). Using optical polarimetry of NGC 1068, Scarrott et al. (1991) found a spiral pattern that was interpreted as delineating the magnetic field geometry in the arm and interam structures of the galaxy (Fig. 2). At FIR wavelengths, however, scattering and Faraday rotation are not a factor. Also, the FIR emission is from dust, and consequently is more closely tied with the total column density of the gas than the relativistic electrons causing the synchrotron emission.



NGC1068: Total flux (color scale) with the inferred magnetic field (LIC map) using HAWC+ observations.

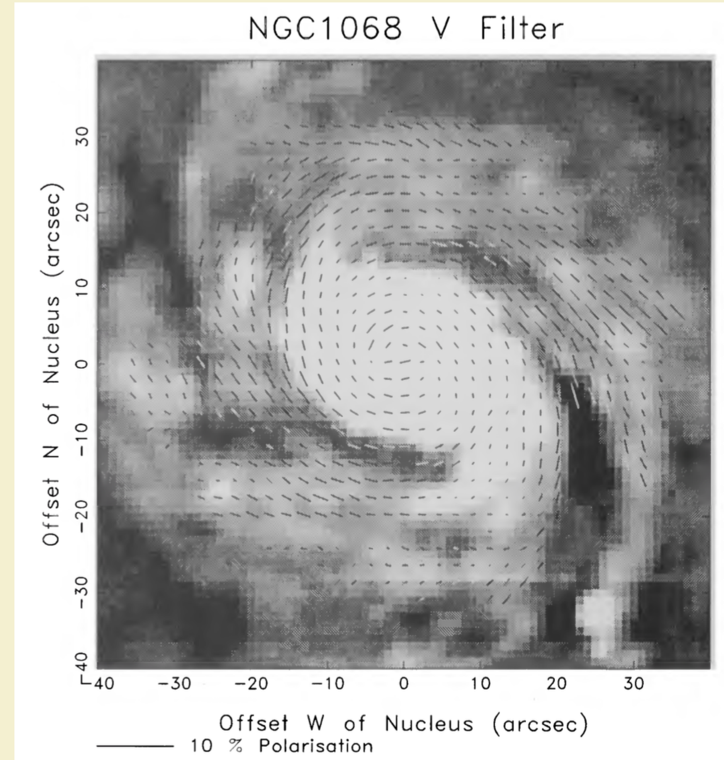
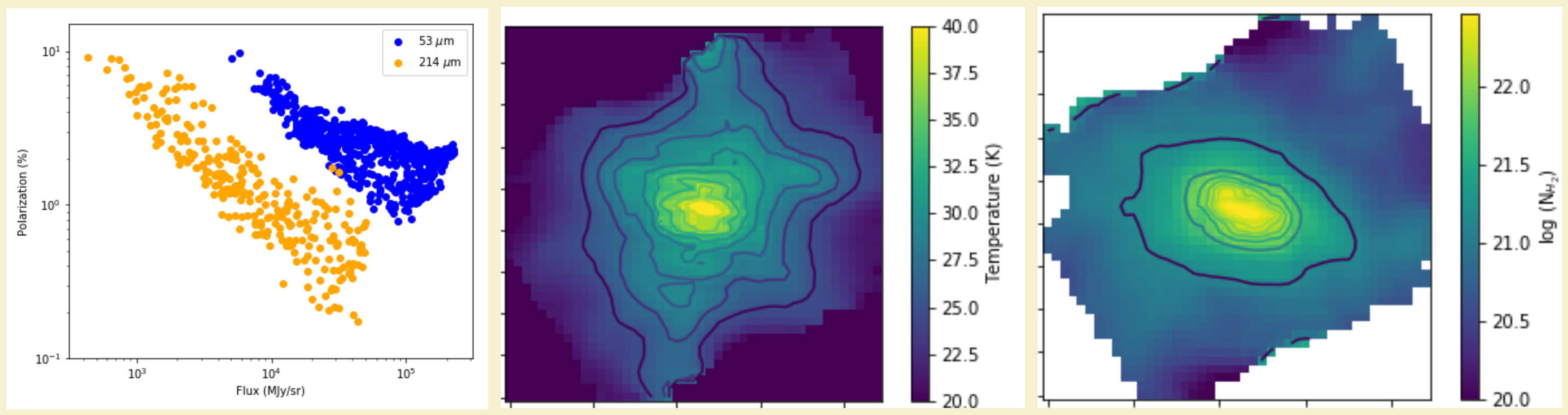


Figure 2: Optical polarization of NGC 1068 showing the large-scale spiral polarized arms (Scarrott et al. 1991). Note the similarity of these vectors with those observed by HAWC+, which indicates that the bulk of the interstellar medium in the disk of NGC 1068 is threaded by a magnetic field that closely follows the spiral arms. However, the optical map is dominated by scattering, which could be a major contaminant.

Polar Magnetic Field

The degree of polarization shows a dependency slightly lower than $I^{-1/2}$ (left panel), which suggest a combination of both a constant and a purely random magnetic field component along the line of sight. Unlike at NIR wavelength (Fig. 1), which is sensitive to the total dust column depth, at FIR wavelengths the hotter dust in the nuclei causes the 53 µm polarization to be dominated by the vertical field in the nucleus. We computed the temperature (middle panel), and column density (right panel) using HAWC+ and *Herschel* observations. We estimate a warm mass of 1-2 10^7 $M_\odot$ in the central 30"x15" (520 x 260 pc) with a visual extinction of A_v ~10.

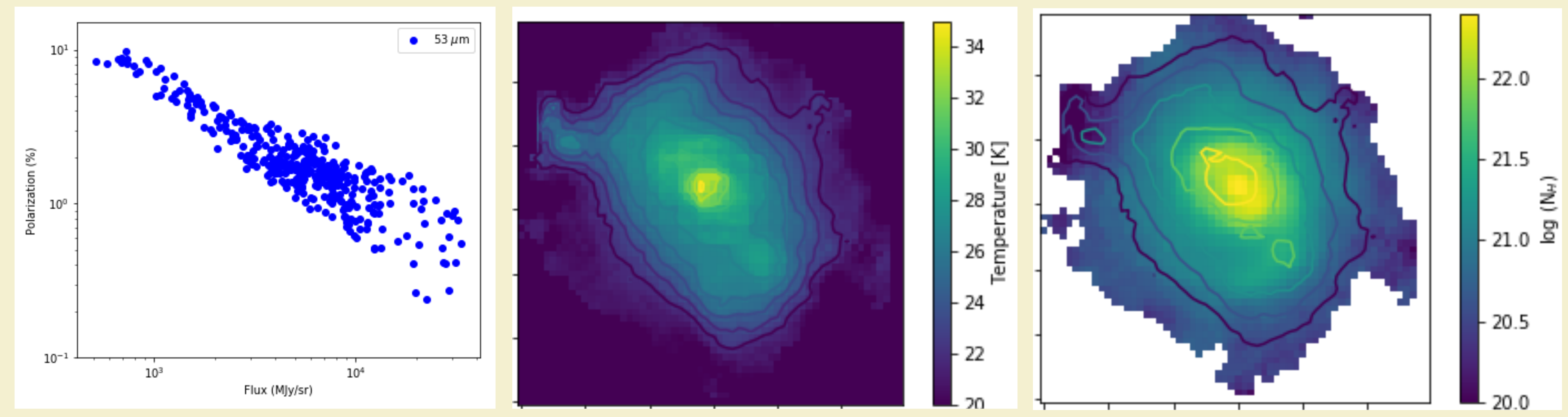


Far-Infrared Observations with SOFIA

M82 and NGC 1068 were observed with the newest SOFIA instrument, the High-resolution Airborne Wideband Camera-plus (HAWC+). We made observations using the chop-nod polarimetric mode at 53 and 89 µm with beam sizes of 4.85" and 7.80", respectively. Final observations provide a total exposure time of 1782s at 53 µm for M82 and 7315s at 89 µm for NGC 1068.

Spiral Magnetic Field

The degree of polarization shows a tight dependency with the total intensity with a power-law index ~0.88 (left panel), which suggests that the large-scale polarization is dominated by a constant magnetic field component along the line of sight. This relation does not hold at the core; there is a slightly lower dependency than $I^{-1/2}$, which may indicate that the jet and active nuclei are influencing the efficiency of dust alignment.



Jones, T. J. (2000, 120, 2920)
Ohyama et al. (2002, PASP, 54, 891)
Shopbell &. Bland-Hawthorn (1988, ApJ, 493, 129)
Telesco, C. M. (1988, ARA&A, 26, 343)
Telesco et al. (1989, ApJ, 343, 13)

If you want to use SOFIA to observe your favorite galaxy, you have until September 7 to submit your proposal

https://www.sofia.usra.edu/science/proposing-and-observing/proposal-calls/cycle-7

Beck, R. & Wielebinski, R. (2013, Planets, stars and Stellar Systems, Vol. 5, ISBN 978-94-007-5611-3)
Scarrott, et al. (1991, MNRAS, 250, 111)