1994ApJ...427L..17P

THE ASTROPHYSICAL JOURNAL, 427:L17–L20, 1994 May 20

THE [N II] 205 MICRON LINE IN M82: THE WARM IONIZED MEDIUM

S. J. PETUCHOWSKI[1] AND C. L. BENNETT
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, MC 685, Greenbelt, MD 20771
AND
MICHAEL R. HAAS, EDWIN F. ERICKSON, STEVEN D. LORD,[2] ROBERT H. RUBIN,[3]
SEAN W. J. COLGAN,[4] AND D. J. HOLLENBACH
Space Science Division, NASA/Ames Research Center, Moffett Field, CA 94035
Received 1993 November 1; accepted 1994 March 9

ABSTRACT

Detection of the 205 μm fine structure line of N II in the nearby starburst galaxy M82 is reported. The intensity within a 54″ (FWHM) beam is $(7.1 \pm 1.2) \times 10^{-19}$ W cm^{-2}. The ratio of the intensity of the recently detected 122 μm line to that of the 205 μm line is $=4.2^{+1.6}_{-1.2}$, significantly larger than the corresponding Galactic value of 1.6 ± 0.3, reflecting higher electron densities within the central 850 pc of M82 in comparison to the *COBE* Galactic average. The 205 μm line profile is consistent with other far-infrared fine-structure line profiles observed in M82. The observations are interpreted in the context of a two-component model of the ionized medium in M82. We find that a component of density as low as ~ 50 cm^{-3} can comprise up to 70% of the total mass of warm ionized gas within the beam. The balance of the ionized mass is comprised of a component of density $\gtrsim 100$ cm^{-3}. A model is explored in which the denser ionized medium constitutes the boundaries of neutral surfaces which border the expanding hot plasma from the nuclear region.

Subject headings: galaxies: individual (M82) — ISM: general

1. INTRODUCTION

The nearby irregular galaxy M82 is characterized by a nuclear region with starburst activity, ionized streamers, and a molecular ring with spurs extending over 500 pc above and below the disk. A blowout from the nuclear region caused by intense stellar winds and/or supernova ejecta is suggested by X-ray plumes (Schaaf et al. 1989), by synchrotron emission (Seaquist & Odegard 1991), and by Hα and other emission-line tracers of warm ionized gas which extend to a height of ∼3–4 kpc (McCarthy, Heckman, & van Breugel 1987). McCarthy et al. associate the off-plane warm ($\sim 10^4$ K) ionized optical emission-line gas with a hot ($\sim 10^6$ K) outflowing wind, attributing the emission to low-velocity shock heating of dense clouds embedded in the hot outflow.

An alternative picture is suggested by the spurlike features of molecular gas emerging perpendicular to the plane of the galaxy which lie just outside the X-ray halo and ridges of the Hα filaments (Nakai et al. 1987). They attribute these structures to a hollow cylinder, or chimney, of molecular material which, like the hot plasma it envelopes, is expanding out of the plane. Photodissociation regions (PDRs) traced by [C II] 158 μm emission (Lugten et al. 1986) are also present several hundred pc above and below the plane.

Atomic fine-structure lines detected in galaxies prior to the present observations predominantly sampled either neutral atomic regions ([C II] and [O I]) (Lugten et al. 1986; Lord et al. 1994a) or more highly ionized regions ([S III], [O III], [N III], and [Ne II]) (Houck et al. 1984; Duffy et al. 1987; Beck et al. 1978) characteristic of H II regions surrounding massive young stars. However, much of the warm ionized medium is now known to extend large distances from the plane and thus far from the population of ionizing stars, both in the Milky Way (Reynolds 1993) and in M82 (see the discussion above). The far-infrared fine-structure [N II] lines trace virtually all of the warm ionized gas since the ionization potential of nitrogen exceeds that of hydrogen by only 0.9 eV. In comparison to the visible [N II] lines, far-infrared fluxes suffer much less from uncertain extinction or uncertainty in the temperature of exciting electrons.

2. OBSERVATIONS AND ANALYSIS

The ${}^3P_1 \rightarrow {}^3P_0$ ground state fine-structure [N II] line at 205 μm was detected in M82 from the NASA Kuiper Airborne Observatory on the nights of 1992 January 16–17 (UT). The 205 μm line, first detected in the Milky Way by the *COBE* FIRAS in its 7° survey of the sky (Wright et al. 1991) and later in the Galactic H II region G333.6−0.2 (Colgan et al. 1993), has subsequently been observed in the laboratory (Brown et al. 1994). The higher-lying ${}^3P_2 \rightarrow {}^3P_1$ transition at 122 μm was also observed in M82, as reported in detail by Lord et al. (1994b). Observations were performed with the NASA/Ames cryogenic grating spectrometer (Erickson et al. 1985), using an array of five stressed Ge:Ga detectors with a spectral resolution of 185 km s^{-1}. The diffraction-limited beam FWHM was 54″, corresponding to 850 pc at M82 for an adopted distance of 3.25 Mpc (Tammann & Sandage 1968).

M82 was observed at the position of the infrared nucleus, $(\alpha_{1950}, \delta_{1950}) = (09^h51^m44^s, +69°55'00'')$ with the beam encompassing the 35″ × 14″ extent of 100 μm emission (Joy, Lester, & Harvey 1987). The beam was chopped at constant air mass with a throw of 6′. Jupiter was used for flux calibration with a diffraction correction applied to account for the relative sizes of M82, for which the 100 μm extent was employed, and the 41″ disk of Jupiter. The wavelengths surrounding the 205 μm line are largely clear of telluric features, and the absolute flux calibration is believed to be better than 30% (3 σ). Wavelength calibration was confirmed by laboratory measurement

---

[1] E-mail: spet@stars.gsfc.nasa.gov.

[2] Postal address: IPAC/California Institute of Technology, Pasadena, CA 91125.

[3] Orion Enterprises.

[4] SETI Institute.

of water lines. The system NEP at 205 μm, including instrumental and atmospheric losses, was 1.6×10^{-14} W Hz$^{-1/2}$. During setup, the CO $J = 13 \rightarrow 12$ line at 200 μm was observed in Orion K-L, the first astronomical detection of this line. The observed line intensity of $(6.1 \pm 0.3) \times 10^{-17}$ W cm^{-2} is consistent with the Watson et al. (1985) model of 750 K postshock gas.

The M82 spectrum shown in Figure 1 reflects a total integration time (including chops off source) of 38 minutes, with the data of each night's observations shown separately. The 205 μm line intensity of $(7.1 \pm 1.2) \times 10^{-19}$ W cm^{-2} corresponds to a luminosity of $(2.4 \pm 0.4) \times 10^6$ $L_\odot$. The reported line intensity is the sum over detectors of actual detected flux. The curve shown is a two Gaussian fit where the widths of two spectral components and their velocity separation have been constrained to be those of the [O III] 88 μm line (Duffy et al. 1987), presented to show consistency of the [N II] 205 μm observations with the dynamical components observed in another cooling line of the warm interstellar medium. The 205 μm broad band continuum is 331 ± 41 Jy. For comparison, a fit to $\nu^{1.5} B_\nu$ ($T_d = 45$ K) by Telesco & Harper (1980) of continuum measurements of the central 50″ of M82 at 41, 58, 78, and 141 μm yields 270 Jy at 205 μm.

Two other positions in M82 were observed. Upper limits ($2\,\sigma$) to emission in the 205 μm line of 2.6×10^{-19} W cm^{-2} and 3.4×10^{-19} W cm^{-2} were found for positions on the minor axis, 40″ SE of the infrared nucleus, and on the major axis, 40″ NE of the infrared nucleus, respectively.

3. RESULTS AND DISCUSSION

Mean electron densities of 120^{+120}_{-80} cm^{-3} (Lugten et al. 1986) and 210 ± 75 cm^{-3} (Duffy et al. 1987) have been derived for the ionized medium in M82 from the ratio of [O III] lines, subject to the simplifying assumption of a single homogeneous ionized component and an assumed range of electron temperature, T_e. We apply a similar methodology, employing a seven-level N II atomic model with rates tabulated by Mendoza (1983) and assuming T_e in the range $(5\text{–}10) \times 10^3$ K, an an ambient far-ultraviolet interstellar radiation field $G_0 = (1\text{–}10^4)$, where G_0 is the 6–13.6 eV UV field intensity, in units of 10^8 cm^{-2} s^{-1} (representative of the local average Galactic FUV flux). In the low-density limit, the theoretical ratio of the [N II] fine-structure emission-line fluxes is $I(122\ \mu\text{m})/I(205\ \mu\text{m}) = 0.7$, while in the dense limit ($n_e \gtrsim 1000$ cm^{-3}), the ratio tends to its thermal equilibrium value of 9.8. From the observed [N II] line intensity ratio, $I(122\ \mu\text{m})/I(205\ \mu\text{m}) = 4.2^{+1.6}_{-1.2}$, we derive a mean electron density of 180^{+209}_{-120} cm^{-3}.

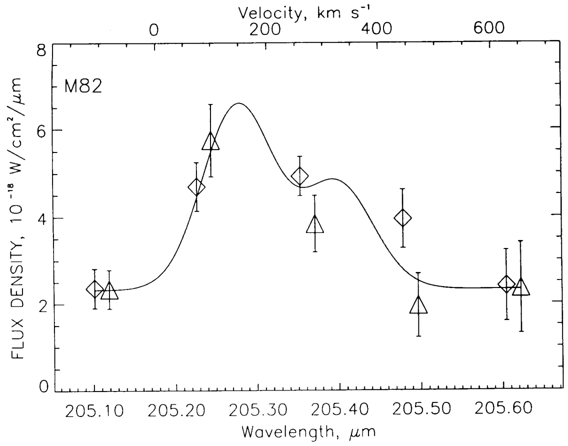

FIG. 1.—[N II] 205 μm spectrum of M82. Diamonds (triangles) represent data of 1992 January 16 (17). A two-Gaussian fit assuming the spectral components of the [O III] 88 μm line (Duffy et al. 1987) is also shown.

Studies of both radio continuum and radio and visible emission lines in M82 have suggested the presence of two distinct components of ionized gas, distinguished both spatially and kinematically. While one component is associated with the central starburst region of the galaxy, the second involves the filamentary material observed off the plane which has been associated with a starburst wind (McCarthy et al. 1987; Götz et al. 1990). Distinct spectral components of the ionized ISM in M82 are also evident in radio recombination lines; Seaquist, Bell, & Bignell (1985) fitted recombination line data and derived both broad (FWHM = 150 ± 20 km s^{-1}) and narrow (FWHM = 60 ± 30 km s^{-1}) spectral components. The broad component is spatially extended and is consistently modeled by a filling factor of order unity and lower electron densities than the narrow component (Seaquist et al. 1985).

As discussed in § 1, large regions of ionized gas in M82 lie outside the central starburst region to heights of 3–4 kpc above the plane. Considering the central region to cover only the 30″ × 20″ area of high obscuration (Waller, Gurwell, & Tamura 1992), it can be expected that the 54″ beam at 205 μm will encompass some of the exterior ionized gas. Since the physical conditions of the exterior ionized gas might differ qualitatively from those typical of the central region, we consider how much of the emission in our beam arises exterior to the central starburst region and treat the exterior gas as a distinct component. The fraction of ionized emission arising from the exterior ionized gas is estimated to be $\sim 11\%$, as derived from the Hα emission maps of Waller et al. (1992) in the following manner. A corrected Hα flux is derived from the observed 3 mm radio continuum emission. The total 92 GHz flux within the aperture synthesis map of Carlstrom & Kronberg (1991) is 0.59 ± 0.09 Jy. Carlstrom & Kronberg have shown that this flux is predominantly free-free emission, a conclusion further supported by Puxley et al.'s (1989) analysis of H53α emission. It corresponds, therefore, to a total Hα line flux of $(1.2 \pm 0.4) \times 10^{-15}$ W cm^{-2}, assuming T_e in the range $(5\text{–}10) \times 10^3$ K. While the Calstrom & Kronberg map is insensitive to emission on a scale exceeding 50″, the 87 GHz flux density of 0.54 ± 0.08 Jy observed within a 75″ beam by Jura, Hobbs, & Maran (1978) provides assurance that the missing flux does not exceed the quoted measurement error.

The Hα flux within the 54″ beam and exterior to the 30″ × 20″ central region has been summed from the CCD image of Waller et al. (1992) and corrected for visual extinction based on the observed [S III]/Hα ratio and for a mean [N II] $\lambda\lambda$6548, 6584 emission contribution of 41%, to derive an Hα flux within the beam attributable to exterior ionized gas of 1.5×10^{-16} W cm^{-2} (W. H. Waller 1993, private communication), or $(11^{+5}_{-3})\%$ of the total Hα flux within the 54″ beam. Though the exterior ionized gas contributes only $\sim 11\%$ to the total Hα flux, the Hα and free-free continuum flux are proportional to $n_e M_i$, where M_i is the mass of ionized gas, so that if the exterior gas is of appreciably lower density, it may represent a correspondingly greater fraction of the ionized mass of the galaxy. This is true, as well, of the 122 and 205 μm flux, since the fine-structure line intensities are $\propto n_e M_i$ only at densities low compared to the critical densities (300 and 40 cm^{-3}, respectively).

1994ApJ...427L..17P

Solutions have been found for which the observed fluxes at 205 and 122 μm are consistent with the 3 mm radio continuum emission, distributed spatially as indicated by the ratio of corrected Hα luminosity inside and outside the central region. Complete ionization and an Orion elemental abundance ratio of [N]/[H] = 6.8×10^{-5} (Rubin et al. 1991) are assumed. For fractional masses of f_1 and f_2 in the exterior and central region, respectively, and n_i electron densities in the respective regions, $f_1 n_1 > 0.12 f_2 n_2$, with the inequality reflecting the formal possibility that a significant fraction of the flux in the central region arises in lower-density gas, although that possibility is unlikely on grounds of pressure equilibrium. We have also neglected the smaller size of the 122 μm beam in the model calculations. The locus of solutions appears as the clear region of Figure 2. For a given n_1 along the abscissa, solutions consistent with observations exist within the indicated range of fractional mass, and with a corresponding second component of density n_2 within the limits shown. In this model, as much as 3% of the ionized gas in M82 can have densities >1000 cm^{-3}, while Houck et al. (1984) used [S III] lines to set a limit of 1%. The model also requires a density in the low-density component in conflict with the upper limit of 34 cm^{-3} which Seaquist et al. (1985) derived from two-component models of free-free radio opacity.

In the model described, n_e of the lower density component must be at least 50 cm^{-3}, in which case it comprises between $\sim$45% and $\sim$70% of the ionized mass, with the corresponding n_e of the higher density component between $\sim$150 and $\sim$180 cm^{-3}. The electron density of the denser component is in all cases $\gtrsim 100$ cm^{-3}, while the total ionized mass, is (1.9–3.2) $\times 10^7\ M_\odot$ for the entire range of solutions found.

A possible interpretation of the denser ionized gas is as an ionized boundary layer (IBL) which coats a neutral component illuminated by ionizing radiation. In this picture, the thickness, w, of an ionization-bounded sheath of a cloud is related to the flux of incident ionizing radiation by

$$w[\mathrm{pc}] = \frac{4.1\ \mathrm{cm}^{-6}}{n_e^2}\left(\frac{T_e}{8000\ \mathrm{K}}\right)^{0.85} F_{\mathrm{ion}}\,, \qquad (1)$$

where $F_{\rm ion}$ is the flux of ionizing photons in units of 4×10^6 cm^{-2} s^{-1}, a number which is representative of the local average Galactic flux (Reynolds 1984). If 30% of the ionized mass of $2.5 \times 10^7\ M_\odot$ is in sheets of thickness w, the area covered by such sheets is $(1.4 \times 10^{10})/F_{\rm ion}$ pc^2. Two possible dispositions of such a surface area might be as the lining of superbubbles and as the interior surface of a hollow cylinder of molecular gas such as posited by Nakai et al. (1987).

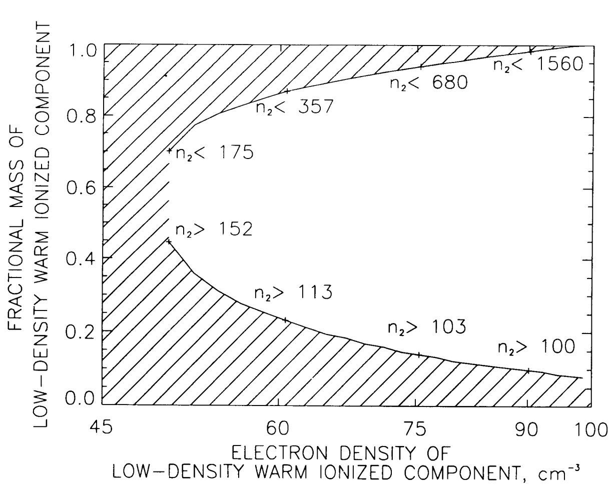

FIG. 2.—Locus of solutions for a two-component model of the warm ionized gas in M82. The density of the higher density component is labeled n_2.

If the IBL is a sheath lining neutral regions, we expected to associate a comparable surface area of PDR with the ionized layer. A PDR mass of $\sim 3 \times 10^7\ M_\odot$ and average density of $\sim 2 \times 10^4$ cm^{-3} have been determined from [C II] 158 μm observations by Lugten et al. (1986). Associating the entire PDR volume of 6×10^4 pc^3 with the IBL surface area, we infer an effective PDR thickness of $4.4 \times 10^{-6} F_{\rm ion}$ pc. Tielens & Hollenbach (1985) show that the [C II] PDR thickness is approximately 0.1 pc for a PDR density of 2×10^4 cm^{-3} and a relatively high incident UV flux. The solution for the ionizing flux gives $F_{\rm ion} \sim 2 \times 10^4$.

We can associate the FUV field intensity with the ionizing field intensity, $G_0 \propto F_{\rm ion}$, at least to first order, neglecting differences in the luminosity function of massive stars. The derived value of $F_{\rm ion}$ is thus consistent with an interpretation of [C II] and CO emission which indicates that the bulk of the neutral ISM in starburst galaxies is exposed to UV fields of $G_0 > 1000$ (Stacey et al. 1991), and, moreover, with the PDR models of Wolfire, Tielens, & Hollenbach (1990), who use ratios of fine-structure lines to determine $G_0 = 10^{3.9 \pm 0.3}$ within the central 330 pc of M82. The picture of neutral sheets is also consistent with the low observed volume-filling factor ($\sim 10^{-4}$ to 10^{-3}) of the neutral gas compared with the beam area-filling factor of $\sim 10^{-1}$ (Lugten et al. 1986). Considering the dense ionized boundary layer as the interface between a superbubble of hot gas and a neutral casing, the equivalent radius of such a superbubble would be $33(F_{\rm ion})^{-1/2}$ kpc, or 230 pc for $F_{\rm ion} = 2 \times 10^4$. Since this is comparable to the size of superbubbles evident in the LMC (Bruhweiler, Fitzurka, & Gull 1991), it is not necessary to posit more than several such superbubbles.

Alternatively, the expanding cylinder of molecular gas (Nakai et al. 1987) has a radius, on the plane, $\sim$200 pc and a vertical extent $\sim$500 pc. By equating the boundary area with the N II area derived above, we obtain a reasonable ionizing flux of $F_{\rm ion} \sim 1 \times 10^4$.

While we cannot distinguish between the foregoing geometries, the identification of a denser component of ionized gas with the periphery of hot regions surrounded by neutral gas is an appealing one. An overall ionzing luminosity of $(1.6 \pm 0.5) \times 10^{54}$ photons s^{-1} is implied by the two-component model limits discussed above, if the entire H II mass is the product of photoionization.

4. COMPARISON WITH THE MILKY WAY

The ratio of the [C II] 158 μm flux reported by Stacey et al. (1991) to the newly detected [N II] 205 μm flux is 20.0 ± 3.4, within the central 50″ of M82, in comparison with a Galactic value of 10.4 ± 1.0 derived from FIRAS (Wright et al. 1991), and lower values within the central Milky Way (Bennett & Hinshaw 1993). Higher PDR area filling factors in M82 may give rise to the enhanced $I(158\ \mu\mathrm{m})/I(205\ \mu\mathrm{m})$ ratio.

The ratio of the [N II] fine-structure line fluxes, $I(122\ \mu\mathrm{m})/I(205\ \mu\mathrm{m}) = 4.2^{+1.6}_{-1.2}$, is significantly larger than the corresponding Galactic value of 1.6 ± 0.3, reflecting higher electron densities within the denser ionized component in the central kpc of M82 compared with the *COBE* Galactic average.

5. CONCLUSIONS

We report a detection of [N II] fine-structure emission in the central 850 pc of M82. We explore the detected emission in terms of a model in which the predominant [N II] emission is provided by two components of the warm ionized medium. The density of one component could be as low as 50 cm^{-3} and account for as much as 70% of the mass of the ionized medium. We show that the detected mass of ionized gas is consistent with a picture either of a hollow chimney through which hot plasma is expelled from the plane of the galaxy or of one or several superbubbles. We look to observations of ionized species off the galactic disk to further constrain our picture of the ionized medium in M82.

We are grateful for the assistance of the staff of the Kuiper Airborne Observatory and particularly that of Allan Meyer. We also thank Bill Waller for his analysis of complementary optical data. Instrument support is provided by NASA under UPN 352, the NASA Airborne Astronomy Program. S. J. P. and C. L. B. acknowledge Guest Investigator support under the same program. S. W. J. C. and R. H. R. acknowledge NASA/Ames Research Center Interchange Grants NCC 2-647 and NCA 2-612, respectively.

REFERENCES

Beck, S. C., Lacy, J. H., Baas, F., & Townes, C. H. 1978, ApJ, 226, 545
Bennett, C. L., & Hinshaw, G. 1993, in Back to the Galaxy, ed. S. S. Holt & F. Verter (New York: AIP), 257
Brown, J. M., Varberg, T. D., Evenson, K. M., & Cooksy, A. L. 1994, ApJ, in press
Bruhweiler, F. C., Fitzurka, M. A., & Gull, T. R. 1991, ApJ, 370, 551
Carlstrom, J. E., & Kronberg, P. P. 1991, ApJ, 366, 422
Colgan, S. W. J., Haas, M. R., Erickson, E. F., Rubin, R. H., Simpson, J. P., & Russell, R. W. 1993, ApJ, 413, 237
Duffy, P. B., Erickson, E. F., Haas, M. R., & Houck, J. R. 1987, ApJ, 315, 68
Erickson, E. F., Houck, J. R., Harwit, M. O., Rank, D. M., Haas, M. R., Hollenbach, D. J., Simpson, J. P., & Augason, G. C. 1985, IR Phys., 25, 513
Götz, M., McKeith, C. D., Downes, D., & Greve, A. 1990, A&A, 240, 52
Houck, J. R., Shure, M. A., Gull, G. E., & Herter, T. 1984, ApJ, 287, L11
Joy, M., Lester, D. F., & Harvey, P. M. 1987, ApJ, 319, 314
Jura, M., Hobbs, R. W., & Maran, S. P. 1978, AJ, 83, 153
Lord, S. D., Hollenbach, D. J., Haas, M. R., Rubin, R. H., & Erickson, E. F. 1994a, in preparation
Lord, S. D., et al. 1994b, in preparation
Lugten, J. B., Watson, D. M., Crawford, M. K., & Genzel, R. 1986, ApJ, 311, L51
McCarthy, P. J., Heckman, T., & van Breugel, W. 1987, AJ, 92, 264
Mendoza, C. 1983, in IAU Symp. 103, Planetary Nebulae, ed. D. R. Flower (Dordrecht: Reidel), 143
Nakai, N., Hayashi, M., Handa, T., Sofue, Y., Hasegawa, T., & Sasaki, M. 1987, PASJ, 39, 685
Puxley, P. J., Brand, P. W. J. L., Moore, T. J. T., Mountain, C. M., Nakai, N., & Yamashita, T. 1989, ApJ, 345, 163
Reynolds, R. J. 1984, ApJ, 282, 191
———. 1993, in Back to the Galaxy, ed. S. S. Holt & F. Verter (New York: AIP), 156
Rubin, R. H., Simpson, J. P., Haas, M. R., & Erickson, E. F. 1991, ApJ, 374, 564
Schaaf, R., Pietsch, W., Biermann, P. L., Kronberg, P. P., & Schmutzler, T. 1989, ApJ, 336, 722
Seaquist, E. R., Bell, M. B., & Bignell, R. C. 1985, ApJ, 294, 546
Seaquist, E. R., & Odegard, N. 1991, ApJ, 369, 320
Stacey, G. J., et al. 1991, ApJ, 373, 423
Tammann, G. A., & Sandage, A. 1968, ApJ, 151, 825
Telesco, C. M., & Harper, D. A. 1980, ApJ, 235, 392
Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 722
Waller, W. H., Gurwell, M., & Tamura, M. 1992, AJ, 104, 63
Watson, D. M., Genzel, R., Townes, C. H., & Storey, J. W. V. 1985, ApJ, 298, 316
Wolfire, M. G., Tielens, A. G. G. M., & Hollenbach, D. 1990, ApJ, 358, 116
Wright, E. L., et al. 1991, ApJ, 381, 200