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Final Technical Report for

NASA Airborne Astronomy Grant NAG 2-372
"Far-Infrared Emission Line Spectroscopy of Planetary Nebulae from the KAO"

Dates of the Project: Oct. 1, 1985 - Sep. 30, 1993
Date of this Report: July 15, 1994

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I. Summary of Scientific Results

General Remarks: The main focus of the overall project was to study the properties of planetary nebulae using far-infrared emission lines. The observations were conducted with the "Cooled Grating Spectrometer" or CGS, a moderate-resolution echelle spectrometer designed and built at the Ames Research Center by a team headed by Drs. Edwin Erickson and Michael Haas, who also collaborated on this research, as did Dr. Michael Werner (then at Ames, now at JPL). During the first few years of the program, the emphasis was on emission lines of doubly-ionized oxygen and nitrogen ([O III] 52 and 88 μm, [N III] 57 μm), which arise in the ionized regions of the nebulae. Starting around 1989, our emphasis shifted to observing fine-structure lines of neutral oxygen and singly-ionized carbon ([O I] 63 and 145 μm, [C II] 157 μm), which arise from predominantly neutral material outside the ionized regions. This program was typically assigned one or two observing flights per year. Because these studies required obtaining a substantial sample of objects in order to reach meaningful conclusions, publication of comprehensive papers summarizing all of the results is still pending. However, numerous interim reports based on the airborne results as well as on closely-related supporting observations have been published during the grant period. The bibliographic information for these reports is given below in the Publications section. An overall summary of the planetary nebula results was presented at the Airborne Astronomy Symposium (20th Anniversary of the KAO) on 8 July 1994; reprints will be provided when available. In parallel with the planetary nebula study, we also observed the [O III] and [N III] lines in several H II regions, and attempted (unsuccessfully) to detect these lines in several old nova remnants and the supernova remnant Cassiopeia A. The overall data set is summarized in Table 1.

A. *Ionized Emission Lines in Planetary Nebulae*

The trio of emission lines [O III] 52, 88 μm and [N III] 57 μm provides an exceptional tool for probing the physical conditions and elemental abundances in ionized nebulae. Historically, these lines were mostly observed in Galactic H II regions, many of which are heavily obscured by interstellar dust such that optical observations are not possible. The motivations for observing the far-infrared lines from the O^{++} and N^{++} ions in planetary nebulae are different than for H II regions, because planetary nebulae are easily observed at optical wavelengths. Precisely *because* one can observe emission lines from the O^{++} ion at optical wavelengths in addition to the far-infrared fine-structure lines, one can use the [O III] spectrum to constrain and determine the physical properties of the gas in unprecented ways. First, the ratio of the two far-infrared lines is an excellent indicator of the density in the main region of the ionized gas, particularly in the range applicable to most planetary nebulae, 10^2-10^4 cm^{-3}. This can be compared to other density indicators, such as the optical lines of [O II] and [S II], that arise in different strata of the nebulae. Second, the intensity ratio of the optical lines [O III] 4959, 5007 Å to the infrared lines is sensitive to the gas temperature. This temperature can be further compared to the value indicated by the ratio [O III] 4363/5007 Å; systematic differences between the two nominal temperatures will occur if the nebula is not isothermal but instead contains gas at a range of temperatures. Correction for the non-isothermal nature of the nebulae results in a larger derived abundance of oxygen with respect to hydrogen, a very important parameter for understanding the evolution of the composition of gas and stars in our Galaxy. We find the following results from observations of nine planetary nebulae (results on two more are still being analyzed): (1). Nebular densities vary from as low as about 100 cm^{-3} to about 10^4 cm^{-3}. The [O III] values show reasonable agreement with those derived from other density indicators, particularly given the fairly large scatter in published densities from the latter. (2) Although earlier work (Dinerstein, Lester, and Werner 1985) seemed to suggest the presence of large spreads in gas temperature, the newer observations (which have more reliable flux calibrations) show that temperature fluctuations, if present, are quantitatively smaller, no more than a few percent typical deviations from the mean value.

The interpretation of the [N III] 57 μm line has long been problematical, because use of the far-infrared lines led to systematically larger estimated values of the elemental abundance ratio N/O than those derived from optical [N II] and [O II] lines. Possible causes of this disagreement include non-collisional excitation of the optical [O II] lines, ionization structure effects (such that the ionization volumes of O^{++} and N^{++} do not coincide), and errors in the atomic parameters, particularly for the [N III] line. Extensive efforts failed to resolve the discrepancy, until the recent publication of a much improved collision strength for the 57 μm transition. Reanalyzing the far-infrared line data on planetary nebulae, we now find the following: (1). Using the new collision strength for [N III] 57 μm, there is no longer any evidence for a systematic difference between the N/O values for planetary nebulae derived from the optical and the infrared; therefore it is likely that this newest collision strength value is correct. This conclusion is based on taking the average of 8 nebulae, since measurement errors do lead to some differences in the values on a case-by-case basis. (2). Planetary nebulae show a wide range in N/O values, as already known from optical work; our values range from about 0.17 (roughly the interstellar value, as seen in H II regions) to 1.2 (for NGC 2440). The enhanced N abundances reflect nuclear processing and mixing in the progenitor star, and give a quantative measure of one channel of enrichment of the interstellar gas.

B. Emission Lines from Neutral Envelopes around Planetary Nebulae

It had long been an unsolved problem as to whether planetary nebulae were "matter-bounded" structures, in which the edge of the ionized region coincided with the boundary of the nebula, or whether there was additional, neutral material outside the ionized gas. Indications that the latter scenario was the usual case were mostly indirect, until astronomers began to detect molecules (H_2 and CO) in a few objects. However, even when molecules are *not* present, it is possible for planetary nebulae to contain significant amounts of neutral matter in *atomic* form, such that the hydrogen is mostly in the form of H I. When juxtaposed with ionized nebulae, such regions are now commonly called "photodissociation regions" and emit primarily in the far-infrared fine-structure lines of [O I] and [C II]. Therefore, we began to systematically observe planetary nebulae, initially only in the 63 μm line of [O I], because the other lines (mainly [C II] 157 μm and [O I] 145 μm) fell outside the operating range of the CGS until around 1990. Our survey of the 63 μm line led to a surprising result: it seemed that almost all reasonably bright planetary nebulae displayed this line, *as if it were the rule rather than the exception for planetary nebulae to contain neutral material.* The intensity of this line scales, within a factor of 2-3, with both the total far-infrared power (as measured by the IRAS satellite) and the radio continuum flux. The few non-detections of the 63 μm line are either for faint nebulae, or for very dense nebulae with low radio fluxes (these objects can be considered "proto-planetary-nebulae" rather than bona-fide planetaries with well-developed ionized zones). There are one or two cases of nebulae in which the 63 μm line was not seen, despite high far-infrared and radio fluxes. These include NGC 6543 and Abell 30, both of which have ionized outer halos, leaving little room for residual neutral material.

The interpretation of the 63 μm emission was unclear at first, except that it demonstrated the presence of neutral material in these planetary nebulae. With the development of the theory of photodissociation regions (hereafter PDRs) by Drs. David Hollenbach and Xander Tielens of

Ames Research Center, we had a context and specific theory for these measurements; the observed intensities of the 63 μm lines were entirely consistent with such an origin for the emission. Pursuing the idea that the line emission arose from PDRs just beyond the boundary of the ionized nebular cores, we went on to measure three lines, [O I] 63, [O I] 145 μm, and [C II] 157 μm, in several planetary nebulae during 1990-92. A preliminary report was given at the AAS meeting in June 1991; since then we have significantly revised some of our quantitative results. We now can summarize our results as follows: (1). The line ratios are somewhat different from those in "interstellar" photodissociation regions. In particular, the [C II] 157 μm line tends to be stronger, probably because the nebulae are carbon-rich. (2). If we correct for the higher carbon abundance, we infer that the material in the photodissociation region is warm ($T > 500$ - 1000 K, but indeterminate beyond that), and dense ($\log n = 3$-4). (3). The masses of these regions are about 0.1 solar masses, comparable to the masses in ionized gas. Thus, the total masses of planetary nebulae are at least a factor of two greater than those measured from ionized hydrogen. They may actually be larger, since the outer parts of the neutral envelopes may be so cool that they cease to emit substantial emission in the [O I] and [C II] lines, and must be observed by other means.

C. Ionic Lines from H II Regions

The Principal Investigator of this program previously participated in a long-term project to measure the N/O abundance gradient across the disk of our Milky Way Galaxy from far-infrared measurements of the [O III] and [N III] lines. That study, published by Lester et al (1987), found that N/O tended to be higher in the H II regions near the galactic center and in the "3-5 kpc ring" than in H II regions in the solar neighborhood. To extend this work, and to help explore the origin of the N/O discrepancy discussed in Section A above, we undertook to observe several H II regions located at larger distances from the Galactic Center than the Sun. We obtained observations of the ionic lines in S 206, S 209, and S 212, and also NGC 604, a giant H II region in M 33. Although the first three objects were observed in 1986-87, not until the new collision strength for the 57 μm line became available in 1992 was there a satisfactory interpretation of the data. The error in the previous value had particularly severe consequences for these H II regions, because at their low densities the derived abundances are particularly sensitive to this parameter. Using the new value, we find that the mean N/O abundance for these three regions, which are located between 12 and 16 kpc from the Galactic Center (assuming a solar galactocentric distance of 8.5 kpc), is $N/O = 0.13$. This is about a factor of two lower than the mean N/O abundance *measured by the same method* for H II regions in the solar vicinity. It indicates that the outer galaxy is slightly nitrogen-deficient compared to the solar neighborhood, and shows that the overall trend for N/O to decline with increasing radial distance extends beyond the solar circle, to the outer galaxy. For NGC 604, we find a gas density from the [O III] lines that is consistent with optical determinations; the N/O abundance has not yet been analyzed.

D. Search for Fine-Structure Lines from Nova Remnants and Cas A

Motivated by the IRAS results on old nova remnants, which seemed to indicate the probability that emission lines contributed to the broad-band infrared emission, we attempted to detect several emission lines, primarily from [O III] and [O I], in several old remnants of stellar explosions. Several papers in the literature had suggested that the extremely metal-rich gas in old nova shells and in the metal-rich clumps of some supernova remnants might cool primarily in the far-infrared lines. We targeted DQ Her, GK Per, and Cas A for this search. Unfortunately, at the time we attempted these measurements, the CGS was not optimally configured for this project; only a fairly high spectral resolution mode was available, covering a small range of velocities; the lower-resolution mode that was installed later, to observe SN 1987A, was not yet available. Therefore, the observations were unsuccessful, but inconclusive. It is likely that these lines will be detected by SOFIA, if they are not first seen by the European Infrared Space Observatory (ISO).

E. Supporting Observations

During the duration of the project, some supporting observations were made with the 107-inch telescope at McDonald Observatory. McDonald is a private observatory operated by the University of Texas at Austin and located in a dark-sky site in western Texas; the PI has frequent, inexpensive access to the facilities there, which include optical and near-infrared spectrometers. This facility was used to support the airborne observations by providing a method to "screen" candidate objects in order to select the best choices for airborne observations and avoid wasting valuable KAO time. For example, optical observations were made of about 7-8 Galactic H II regions prior to KAO flights, in order to determine which objects had sufficiently strong [O III] lines in the optical, so that the far-infrared [O III] and [N III] lines would be detectable. For the study of neutral envelopes in planetary nebulae, ground-based observations were made to search for evidence of Na I absorption lines in the optical, and H_2 lines in the near-infrared, before selecting sources in which to observe the far-infrared fine-structure lines. These supporting observations helped conserve the limited airborne observing time by avoiding wasting time on undetectable or uninteresting sources, and will also be useful in the interpretation and modelling of the nebulae. In some cases, the supporting observations were sufficiently valuable in their own right to warrant publication (see publication list).

II. Publications based on Airborne & Supporting Observations

1. "Far-Infrared Line Observations of Planetary Nebulae: The [O III] Spectrum," Dinerstein, H.L., Lester, D.F., and Werner, M.W., 1985, Astrophys. J., **291**, 561.

2. "Detection of [O I] 63 μm Line Emission from Planetary Nebulae," H.L. Dinerstein, H.B. Ellis, M.R. Haas, and M.W. Werner, 1985, Bulletin Amer. Astr. Soc., **17**, 908.

3. "Abundance Studies of Oxygen and Nitrogen in Nebulae: Uses of the Far-Infrared Emission Lines," Dinerstein, H.L., 1986, Pub. Astron. Soc. Pacific, **98**, 989.

4. "Near-Infrared Spectroscopy of Planetary Nebulae: How Strong is the H_2 Emission?" Dinerstein, H.L., Carr, J.S., Coleman, H.H., Harvey, P.M., and Lester, D.F., 1986, in Abstracts of Contributed Papers: Workshop on Interstellar Processes, eds. D.J. Hollenbach and H.A. Thronson, Jr. (NASA), pp. 43-44.

5. "Observations of Infrared Emission from a Fast Moving Knot in Cassiopeia A," Dinerstein, H.L., Lester, D.F., Rank, D.M., Werner, M.W., and Wooden, D.H., 1986, Astrophys. J., **312**, 314.

6. "Far-Infrared Measurements of N/O in H II Regions: Evidence for Enhanced CN Process Nucelosynthesis in the Inner Galaxy," Lester, D.F., Dinerstein, H.L., Werner, M.W., Watson, D.M., Genzel, R., and Storey, J.W.V., 1987, Astrophys. J., **320**, 573.

7. "Near-Infrared Spectroscopy of Nova Herculis 1987," Dinerstein, H., Coleman, H., and Lester, D., 1987, International Astronomical Union Circular, No. 4425.

8. "Infrared Line Emission from the Giant Extragalactic H II Region NGC 604," H.L. Dinerstein, E. F. Erickson, M.R. Haas, and M.W. Werner, 1987, Bulletin Amer. Astr. Soc., **19**, 1018.

9. "Detection of Fluorescent Molecular Hydrogen Emission in the Planetary Nebula Hubble 12," Dinerstein, H.L., Lester, D.F., Carr, J.S., and Harvey, P.M., 1988, Astrophys. J. (Letters), **327**, L27.

10. "Scattering of Sodium D Photons by Neutral Gas in the Planetary Nebula BD+30 3639," Dinerstein, H.L. and Sneden, C., 1988, Astrophys. J.(Letters), **335**, L23.

11. "Spectroscopic Observations of the High-Ionization Planetary Nebula NGC 2242 and the H II Region K4-45," Garnett, D.R., and Dinerstein, H.L., 1988, Astron. J. **95**, 119.

12. "N/O Abundances in Planetary Nebulae from Far-Infrared Line Observations," Dinerstein, H.L. and Werner, M.W., 1989, in Planetary Nebulae: IAU Symposium 131, ed. S. Torres-Peimbert (Dordrecht: Reidel), p. 214.

13. "Fluorescent H_2 Emission in the Planetary Nebulae BD+30 3639 and Hb 12," Dinerstein, H.L., Carr, J.S., Harvey, P.M., and Lester, D.F., 1989, ibid, p.206.

14. "The Composition of Nebulae: New Views from Infrared Spectroscopy," Dinerstein, H.L., 1989, Bulletin Amer. Astr. Soc., **21**, 1184 (from an hour-long invited talk).

15. "Near-Infrared Spectroscopy of Classical Novae in the Coronal Phase," R.A. Benjamin and H.L. Dinerstein, 1990, Astron.J., **100**, 1588.

16. "Abundances in Extragalactic H II Regions," Dinerstein, H.L., 1990, in The ISM in External Galaxies, eds. H.A. Thronson, Jr., and J.M.Shull (Dordrecht: Kluwer), pp. 257-285.

17. "A Survey of Na I in Neutral Envelopes around Planetary Nebulae," Dinerstein, H.L., Sneden, C., and Uglum, J. 1990, Bulletin Amer. Astr. Soc., **22**, 1271.

18. "Neutral Matter in Planetary Nebulae," Dinerstein, H.L., 1991, Pub.Astr.Soc. Pacific, **103**, 861.

19. "Far-Infrared Line Emission from the Neutral Envelopes around Planetary Nebulae," Dinerstein, H.L., Haas, M.R., Werner, M.W. 1991, Bulletin Amer. Astr. Soc., **23**, 915.

20. "The Evolving Near-Infrared Spectrum of Nova Cyg 1992: The Transition to the Coronal Phase," Dinerstein, H.L., Benjamin, R.A., Gaffney, N.I., Lester, D.F., and Ramseyer, T.F. 1992, Bulletin Amer. Astr. Soc., **24**, 1189.

21. "Measurements of the Far-Infrared [N III] and [O III] Lines in the Outer-Galaxy H II Regions S 206, S 209, and S 212," Dinerstein, H.L., Haas, M.R., Erickson, E.F., and Werner, M.W. 1993, Bulletin Amer. Astr. Soc., **25**, 850.

22. "The Evolution of the Infrared Spectra of Classical Novae," Dinerstein, H.L. and Benjamin, R.A. 1993, Revista Mexicana de Astrofizika, **27**, 33-40.

23. "Infrared Emission Lines," Dinerstein, H.L., 1994, invited review at "The Analysis of Emission Lines" conference at the Space Telescope Science Institute, Baltimore MD, 16-18 May 1994; also to be a chapter in the Proceedings volume, Cambridge University Press.

24. "Far-Infrared Emission Lines from Planetary Nebulae," Dinerstein, H.L., Haas, M.R., Erickson, E.F., and Werner, M.W. 1994, contributed oral paper at the Airborne Astronomy Symposium, NASA Ames Research Center, Moffett Field CA, 6-8 July 1994; to be published in the Proceedings.

Table 1. Observing Log by Object

Nebula	RA, Dec.	PK No	Date	Calibrator	Ionized Lines	Neutral Lines
Planetary Nebulae						
NGC 40	0010+72	120+09	18 Dec 90	Mars		63, 145, 157
			14 Jan 92	Jupiter		63, 145, 157
NGC 1535	0411-12	206-40	14 Jan 92	Jupiter		63
IC 418	0525-12	215-24	02 Feb 86	Orion	52, 57	63
			31 Jan 87	Orion	52, 88, 57	
			18 Dec 90	Mars		63, 145, 157
			14 Jan 92	Jupiter		63, 34
NGC 2346	0706-00	215+03	02 Feb 86	Orion	52, 57	63
			31 Jan 87	Orion	52, 88, 57	
NGC 2392	0726+21	197+17	31 Jan 87	Orion	52, 88, 57	63
			14 Jan 92	Jupiter		63
NGC 2440	0739-18	234+02	02 Feb 86	Orion	52, 88, 57	63
			01 May 91	Saturn		63, 145, 157
Abell 30	0844+18	208+33	02 Feb 86	Orion	52	63
NGC 4361	1221-18	294+43	01 May 91	Saturn	52, 88	
IC 3568	1231+82	123+34	14 Jan 92	Jupiter		63
			16 Jun 92	Saturn		157
IC 4406	1419-43	319+15	01 May 91	Saturn	52, 88, 57	63
NGC 6210	1642+23	043+37	08 Aug 86	Mars	52, 88, 57	
NGC 6302	1710-37	349+01	08 Aug 86	Mars	52, 88, 57	63 (+map)
			01 May 91	Saturn	52, 88, 57	63, 145, 157, 34
NGC 6543	1758+66	096+29	24 June 87	Jupiter	52, 88, 57	63
			11 July 90	Mars	52, 88, 57	63
			16 Jun 92	Saturn	52, 88, 57, 33, 18	
NGC 6572	1809+06	034+11	08 Aug 86	Mars	52, 88, 57	
			08 Aug 89	W3 OH		63, 145, 157
			11 July 90	Mars		63, 145, 157
			16 Jun 92	Saturn		63, 145, 34
NGC 6790	1920+01	037-06	08 Aug 86	Mars		63
Vy 2-2	1921+09	045-02	11 July 90	Mars		63
BD+30 3639	1932+30	064+05	08 Aug 89	W3 OH		63, 145, 157
			11 July 90	Mars		63, 145, 157

IC 4997	2017+16	058-10	08 Aug 89	W3 OH		63, 157
			11 July 90	Mars		157
NGC 7009	2101-11	037-34	26 June 87	S140	52, 88, 57	
NGC 7027	2105+42	084-03	08 Aug 86	Mars		63 (+map)
			26 June 87	S140		63, 118
			08 Aug 89	W3 OH		63, 145, 157, 118, 153
			11 July 90	Mars		63, 145, 157,
153						
NGC 7662	2323+42	106-17	14 Jan 92	Jupiter	51	63
Hubble 12	2323+57	111-02	24 June 87	Jupiter		63, 157
			11 July 90	Mars		63, 157

ProtoPlanetary Nebulae & Post-AGB Stars

GL 618	0439+36	166-06	02 Feb 86	Orion		63
			31 Jan 87	Orion		63
			18 Dec 90	Mars		157
			14 Jan 92	Jupiter		63, 34
M 2-9	1702-10	010+18	16 Jun 92	Saturn		63, 145, 157, 34
GL 2688	2100+36	080-06	16 Jun 92	Saturn		63, 118, 153, 200
89 Her	1753+26		16 Jun 92	Saturn		63
HD 161796	1743+50		18 Jun 92	Saturn		63

H II Regions

S 206	31 Jan 87	Orion	52, 88, 57	
S 209	02 Feb 86	Orion	52, 88, 57	
S 212	31 Jan 87	Orion	52, 88, 57	
NGC 604 (in M33)	31 Jan 87	Orion	52, 88	
	11 July 90	Mars	57	

Novae and SNR's

Cas A	08 Aug 86	Mars		63
	02 Feb 86	Orion		63
DQ Her	08 Aug 86	Mars	51	
	26 June 87	S140	88	
GK Per	02 Feb 86	Orion	88	63