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ANNUAL REPORT

for the period 1 May 1983 through 30 April 1984

Contract NAS9-16596

for Research on

IMAGERY AND SPECTROSCOPY OF SUPERNOVA REMNANTS AND H II REGIONS

Submitted to

NASA Lyndon B. Johnson Space Center

by

Rice University, Houston, TX 77251

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1. INTRODUCTION

This report describes basic research on supernova remnants done at Rice University during the period 1 May 1983 through 30 April 1984 under contract NAS 9-16596 with the NASA L. B. Johnson Space Flight Center. The Principal Investigator for this research was Dr. Reginald J. Dufour, Associate Professor of Space Physics and Astronomy. The Co-Investigator was Dr. Donald P. Cox, Senior Research Scientist of Space Physics and Astronomy. Graduate students J. Jeff Hester and R. L. Pennington also worked on aspects of the research during this period. The Technical Monitor for this program was Scientist-Astronaut Dr. Robert A. R. Parker of NASA-JSC.

2. RECENT SNR RESEARCH HIGHLIGHTS

In this section we will briefly review some of the research accomplishments on SNRs, and resulting publications, made during past year which were supported in part by the current and previous contracts.

2.1. HIGH RESOLUTION SPECTROSCOPY

In 1982 February Peter O. Shull, Jr. completed a Ph. D. dissertation on the analysis of echelle spectra of galactic and extragalactic supernova remnants. It included the results of an analysis of all of the photographic echelle spectra of the Cygnus Loop and IC 443 SNRs previously obtained by Parker and T. Gull at KPNO, along with newer echelle spectroscopy of SNRs Puppis A and Vela X in the Galaxy and of N49 and N63a in the Large Magellanic Cloud. Four papers describing the results have appeared in publication. They are:

"Velocity Dispersions of Knots in the Cygnus Loop and IC 443", by P. O. Shull, Jr., R. A. R. Parker, T. R. Gull, and R. J. Dufour. 1982, Astrophysical Journal, 253, 682.

"Velocity Dispersions of Knots in Vela X and Puppis A", by P. O. Shull, Jr. 1983, Astrophysical Journal, 269, 218.

"The Structure and Kinematics of N63A and Associated H II Regions", by P. O. Shull, Jr. 1983, Astrophysical Journal, 275, 592.

"The Structure and Kinematics of N49", by P. O. Shull, Jr. 1983, Astrophysical Journal, 275, 611.

Dr. Shull also presented papers on these data at the 161st AAS meeting in Boston, at IAU Symposium No. 101 in Venice, and gave numerous colloquia in Europe during 1982-83 while a postdoctoral research associate at the Max-Planck-Istitut fuer Astronomie in West Germany. During this period he extended his studies of supernova remnants, including analysis of additional data acquired while at Rice which was supported in part by NASA-JSC. Currently, he is a research associate at Arizona State University.

2.2. RASTER SPECTROPHOTOMETRY OF THE CYGNUS LOOP

Most of our effort during the past two years has concentrated on the analysis of image-tube photographs of a region in the eastern edge of the Cygnus Loop SNR taken through interference filters by Parker in 1976 using the KPNO 0.91m telescope at Kitt Peak. The basic reduction and analysis of these data has been completed and the results published in a lengthy and colorful paper:

"Digital Analysis of Narrow Band Imagery of the Cygnus Loop", by J. Jeff Hester, Robert A. R. Parker, and Reginald J. Dufour 1983, <u>Astrophysical Journal</u>, 273, 219.

A reprint of this important paper is attached to this report. This study was also presented as a thesis for the M.S. in Space Physics and Astronomy at Rice by graduate student Jeff Hester. He also presented a paper on this topic at the 162nd AAS meeting in Minneapolis in 1983 June.

It is significant to note that this study marked the first quantitative imagery analysis of a region in a SNR. As such, a number of important conclusions about the optical structure and spectrum of SNRs in their radiative phase of evolution resulted from the study -- some being at odds with those of previous investigations based on spectroscopy of selected areas of the Cygnus Loop. Just as significant, however, was the presentation of data on the optical structure of a SNR in a manner unique to that of previous studies. While the study showed that the spectral characteristics of the Cygnus Loop could, for the most part, be explained by current steady-flow models for shocks in the range of velocities from 60 km s^{-1} to about 120 km s^{-1}, it also pointed out many inconsistencies with current models, and also noted the importance of non-steady flow situations apparent at the outer or "leading" edges of the remnant, where the shock velocities seem to be in excess of 120 km s^{-1}.

Since this study raised as many questions as it answered, a significant part of our current and projected future SNR research is directed towards these questions related to SNRs in general and the Cygnus Loop in particular.

2.3. RESEARCH ON SNR PROGENITORS

Research on the progenitor stars of SNRs is also of interest at Rice. Recently, Rice graduate student Rob Pennington, former Rice professor R. J. Talbot, and the PI have used spatially resolved UBVR imagery maps of the spiral galaxy M83 in conjunction with archival plates of two historical supernovae in M83 to estimate the masses of the SN progenitors from a study of the local stellar population characteristics in the immediate vicinity of the SNe locations. Our first paper on SN1923a and SN1957d appeared in the 1982 November A. J. (Pennington, Talbot, and Dufour 1982). From the application of cluster model evolution tracks to the interpretation of pixel-by-pixel data in the immediate vicinity of the SNe, we estimated the progenitor masses of SN1923a and SN1957d to be 18(+22, -8) Mo and 11(+5, -2) Mo, respectively. This study was the first of its kind in using such techniques to estimate SNe progenitor masses, a subject for which little quantitative information exists.

Independently of these studies, Cowan and Branch (1982) published a 20cm VLA radio map of M83 which showed two unresolved radio sources in the disk. Using the approximate positions of recorded SNe in M83 from the literature, they found no coincidence between the positions of the radio sources and any of the four recorded SNe in M83. However, since we were able to obtain much improved positions (believed accurate to about 1-2 arc sec) for two of the SNe in M83 from astrometry of the original discovery plates, we subsequently published (Pennington and Dufour 1983) evidence that one of the unresolved radio sources is indeed the remnant of SN1957d (positions agree to within 2"). This is only the fourth radio detection of a postoutburst SNR in external galaxies (SN1970g in M101, SN1979c in M100, and SN1980K in NGC 6946 are the others) and the oldest identified to date. We also reported the characteristics of the stellar population in the region surrounding the second unresolved radio source in M83 discovered by Cowan and Branch, which apparently has no previously recorded SN counterpart.

3. STATUS OF CONTINUING RESEARCH PROGRAMS

3.1. UV/OPTICAL/RADIO/X-RAY IMAGERY OF SELECTED REGIONS IN THE CYGNUS LOOP

The completion of the digital mapping study by Hester, Parker, and Dufour (1983, hereafter referred to as HPD) of a 5 X 10 arc minute region in the southeastern edge of the Cygnus Loop makes it possible, for the first time, to quantitatively compare the optical structure of a SNR to that mapped at other wavelengths such as the radio and X-ray spectral regions. With this in mind, we have contacted other investigators who might have such data and have taken collaborative efforts in this direction. Bill Ku of Columbia University has Einstein HRI and IPC data of the entire Loop and has sent us HRI imagery of the field studied by HPD for comparison. John Dickel of the University of Illinois has sent us a VLA radio map of a region just to the north of the HPD region. John Raymond of the Center for Astrophysics at Harvard is collaborating with us in obtaining IUE spectroscopy of astrophysically unique locations in the HPD region of the Cygnus Loop, as well as collaborating closely with Cox in the updating and improving of his outstanding SNR model code to hopefully better match the HPD observations, as well as in the development of improved shock wave models for the interpretation of the data at all wavelengths. Lastly, Rob Fesen of Colorado has expressed an interest in collaboration whereby we would be able to use his extensive ground-based spectrophotometry of numerous regions in the Loop for both calibration and interpretation purposes.

Unfortunately, while significant UV, radio, and X-ray data already exist on the Cygnus Loop, it is for the most part a heterogeneous sample of various locations in this large object. Therefore, we have acquired, and are currently analyzing, "new" imagery and spectroscopic data on other regions in the Loop. These data were obtained by Dufour and Hester at KPNO during the summer of 1983 and by Dufour at Lick Observatory during the summer of 1984. These new data and analyses are directed at answering some of the questions remaining after the HPD study in particular; and more generally, are directed towards a better understanding of the basic astrophysics of SNRs. A few examples of currently existing questions about the Cygnus Loop and basic problems related to the astrophysics of SNRs is discussed in what follows.

One of the major points made by HPD is the catagorization of surface brightness enhancements in the Loop as seen in the light of different lines into two types. Type II features showed enhanced emission over background only in lines of high stages of ionization (chiefly O^{++}). They appeared to be regions in which shock waves with $v \approx 100$ km s^{-1} recently (probably within the last few hundred years) began propagation into a density high enough for the incomplete cooling region to be optically visible ($n_0 \gtrsim 1$ cm^{-3}).

On the other hand, Type I features show enhanced emission in all visibly identifiable stages of ionization over spatially unresolvable scales (about 3 arc seconds = 0.011 pc for a distance of 770 pc). They appear to be the complete cooling and recombination regions of shocks with $v \approx 100$ km s^{-1} which have been propagating in densities $\gtrsim 1$ cm^{-3} for more than a few hundred years. Spectra like those of Type I features provide a diffuse background which appears to derive from superposition and line of sight effects from such features not viewed edge on.

The spectra of Type I emission varies systematically away from the outer edge of the remnant in a manner that is independent of the local surface brightness. One gets the impression that the spectra of regions farther from the front derive from slower shock waves, indicating either lower driving pressures or denser preshock gas.

Our expectation with regard to the radio emission is that it arises via the Van der Laan mechanism (Van der Laan 1962): compression of ambient superthermal electrons and magnetic field, accompanied by betatron acceleration of the electrons. The degree of enhancement of the emission over the galactic background is a sensitive function of compression in this mechanism. The radio emission should thus be brightest where the compression is large, in the coolest parts of the recombination region. It should thus be expected to track the optical emission from the last ions to remain, namely [O I] and [S II] lines. If quantitative comparison can be made reliably, both the optical and radio emission will have the same geometrical projections. But the optical lines are proportional to the rate of passage of material through the shock whereas the radio integrates over the total amount of matter already in the dense post recombination shell. Their ratio would then be a measure of the maturity of each filament. This idea should be easily testable in filaments which have well developed bright centers, tapering to invisibility at their ends.

It is strongly suspected that the radio surface brightness should correlate quite poorly with Type II features in which we suppose that full compression has not yet been reached. There are, in fact, intermediate features spanning the range between Type I and Type II in the original HPD field. If a similar range can be found in the proposed CCD results for the VLA field, one expects a very strong correlation between type designation of optical features and the ratio of radio to [O III] surface brightness.

There is additionally the possibility that new cosmic ray electrons are accelerated in the shock front. These fresh particles should, however, undergo further acceleration as the magnetic field is severely compressed in the recombination region. The overall picture remains qualitatively unchanged, but the normalization to the galactic emissivity would be affected. This effect could complicate the interpretation.

A similarly worrisome, albeit interesting, possibility is that the strong compressions of material with an initially chaotic magnetic field could lead to regions in which magnetic field annihilation is taking place. This could provide additional energy sources and particle acceleration in unexpected places as well as local "hot" spots of synchrotron emission. One possible tell-tale sign of this sort of behavior might be such bright spots in what HPD called Type I.5 features. These features have been interpreted as incomplete, but the post shock flow actually has two distinct zones. There is an initially cooling zone in which the temperatures falls to just over 10^4 K. In this zone the UV and [O III] lines arise. Then there is a cooler (T just under 10^4 K) photoionized zone which reprocesses much of the ionizing UV before final recombination. The transition between these two is a region of sudden compression and is marked by very bright [O II] emission. Features which show both [O III] and bright [O II] but weak Hα are Type I.5 and should have relatively complete initial cooling zones but far from complete photoionization zones. Without local particle acceleration of some sort, these features should show much weaker radio emission than fully developed Type I features. If instead they show seemingly random bright patches, we may have isolated a new phenomenon in the Cygnus Loop's repertoire. An odd patchyness of radio emission in otherwise smooth Type I filaments could be similarly revealing.

The Einstein HRI and IPC maps of the Cygnus Loop, when compared with the data discussed above, may provide a unique opportunity for an overall picture of the Cygnus Loop edge situation. We are particularly pleased that Bill Ku has agreed to collaborate with us in this endeavor, and communication of data between us has already begun. The demonstrated power and versatility of the RUPPS facility makes it possible to align, scale, and overlay data in a manner essentially limited only by our imagination. This should enable us to make comparisons of the maps at various wavelengths in a quantitative and detailed manner limited only by the quality of these new data themselves.

Tucker (1971) showed that the overall spectrum and surface brightness of the Cygnus Loop X-rays implied a shock velocity of roughly 300-400 km s^{-1} into a preshock density of about 0.15 cm^{-3}. Cox (1972) showed that the optical filaments implied shock velocities of about 100 km s^{-1} into preshock densities of roughly 5 cm^{-3}. Both calculations implied roughly the same system pressure, a few times 10^{-10} dyn cm^{-2}. McKee and Cowie (1975) suggested that both interpretations were true, and could be reconciled by the existence of small dense cloudlets embedded in a lower density intercloud medium. As the blast wave swept over the ensemble, the main shock traveled at about 300 km s^{-1} through the intercloud component, while slower shocks, driven by roughly the same high pressure, penetrated the clouds (see also DeNoyer 1975).

There has been some argument since as to just what scale the clouds needed to have in order to satisfy the optical observations. Fesen, et al. (1983) interpret their optical data as implying quite small clouds which were rapidly shocked and subsequently cooled and recombined as units rather than having complete cooling and photoionized zones within each. The cloud size required was less than 10^{16} cm. By contrast, HPD explain similar optical data with much larger clouds; clouds whose scales are comparable to filament lengths rather than their widths. Neither sort of cloud (or cloudlet) is typical of the interstellar medium mass distribution, particularly not with the frequency needed to account for the sheer numbers of optical filaments observed. There is a strong hint that the Cygnus Loop pre-explosion enviroment may have been considerably rearranged by the presupernova star. This was apparent from the H I map of DeNoyer (1975), as well as the overall configuration of the Loop; the high local densities found at great distances from the galactic plane, and to some extent expected (after the fact) from the ability of some stars to generate local bubbles via their winds before becoming supernovae (c. f., McCray and Snow 1979).

What can we learn from the X-ray emission? Currently, the data is being examined for several trends. One expectation is that over the spatial region in which the Type I filaments suggest a pressure gradient, the diffuse X-rays should show a corresponding surface brightness gradient. The immersion of the clouds in a shock heated intercloud component is the relevant picture. Where the intercloud component pressure is low, its X-ray brightness, in addition to the [O II] and [S II] measurements, may paint a largely compatible picture.

The X-ray maps are also being examined for features which correlate with the bright optical features. At first glance, no such correlation would be expected. The shock waves which are responsible for the optical filaments are much too slow to generate X-ray emitting gas. On the other hand, Cox (1972) makes the point that the remnant shock waves decelerate with time and that just inward of shock waves traveling at about 100 km s^{-1} is gas that was heated by a shock wave traveling much faster. This perspective is particularly important now that it is relatively clear that clouds of rather high density have been "hit" in the last few hundred years (i.e., as indicated by HPD's Type II features). Just upstream, that is inward, of such clouds is intercloud material that was very recently hit by a much faster shock, and possibly also by a reflected shock. It could be exceptionally bright in X-rays. It might also show quite bright UV or EUV emission. In principle one might expect to find a thin X-ray ghost inward of each optical filament. One definitely expects a transition through the relevant temperature range. What is unclear is whether such ghosts will be apparent against the overall emission of which they are a part. The first guesses are that the ones associated with the most recently encountered clouds, pure Type II, will be the brightest and that even if such ghosts do not stand out in brightness, they may show up as local minima in the X-ray hardness. That is, the transition should show material at lower temperatures and higher densities than the general background emission, leading to a local weighting of X-ray apparent temperature closer to 10^6 °K than the 2 - 3 X 10^6 °K seen generally.

Not all students of the Cygnus Loop fully believe the picture of the cloud-intercloud distinction used to explain the observations. Another possibility is that the explosion took place in a low density bubble around which a few very large clouds were arrayed. It is disconcerting that these clouds seemed to need a very symmetrical arrangement around the Loop, but since recognizing the possible influence of a presupernova wind, this difficulty has been less bothersome.

In this picture, the Cygnus Loop shock wave propagated rapidly in a low density medium with no appreciable optical emission until quite recently, when in some directions it began to encounter the corrugated edges of rather extended clouds -- clouds with scales of several parsecs. The shock wave then began to slow quite suddenly. In directions in which it has not yet encountered the cloud boundary, the emission is primarily in X-rays, the shock velocity is high. In directions in which it has recently encountered a cloud, one will see Type II filaments. Finally, in those directions in which it hit a cloud more than a few hundred years ago, Type I filaments will now be seen.

The overall appearance of this scenerio is very little different from that of the medium sized cloud picture. The spatial separation expected between extreme Type II filaments and the onset of Type I filaments observed by HPD is roughly the distance a 300-400 km s^{-1} shock will travel in a few hundred years. What is different is that the locus of all shock wave positions will be a single closed surface. Convergences of shocks behind clouds and pressure driven shocks propagating back into clouds passed by the main blast wave in the intercloud component will not be found. This may be quite important because in the midsized cloud picture individual clouds are spatially resolved and where the main shock has completely passed, a cloud ought to be enveloped by shocks, with the stronger ones penetrating the inward upstream side and the weaker ones pushing into the outward downstream side. As yet, this geometry has not been seen.

What would then be expected of the X-ray emission? Well, imagine a corrugated cloud boundary hit by a fast shock. In places where the shock hits first, we now see Type I spectra. In places hit more recently, we now see Type II spectra. In places not yet hit, we see the "main shock" or "blast wave" or "intercloud shock" generating X-rays. In addition, somewhat softer X-ray ghosts are expected inward of the optical filaments and weaker, but harder, X-ray emission is expected from the "intercloud" material heated sometime ago. That is, in the absence of all cloud structure, the X-ray spectrum decreases in brightness away from the edge, but increases in hardness due to the negative temperature gradient in a blast wave.

The overall superposition of all of these processes is complicated, but there are things which can be looked for. For example, by locating a filament which is basically Type II, but which grades in [O II] strength along its length, one is perhaps able to follow a progression of recentness of encounter. At the end of such a visible filament, where [O II] has completely disappeared and [O III] has become very faint, one could look for an extension in the UV. Beyond that, one expects to find the location at which the main shock is just *now encountering relatively dense material*. One could there hope to see an X-ray enhancement of particularly low temperature. It will be low for several reasons: lower postshock temperatures are being achieved, and since the material is very recently heated, both electron temperature and ionization will be lower than expected for a equilibrium situation.

Another (our last) expectation is that the ends of some Type II filaments should perhaps lengthen rather rapidly with time due to a scissor effect between shock angle and cloud boundary.

3.2. UV/OPTICAL SPECTROSCOPY OF THE CYGNUS LOOP "SPUR"

One particular Type I feature, designated as the "spur" (c.f., Figures 2, 6, 7, and 16 of HPD) is a region of special interest to us because it seems to be the best example of a "clean" feature uncomplicated by geometrical effects for which the density and shock velocity seem to vary rather uniformly along its length (which manifests itself as a smooth variation in the [O III]/Hα ratio along its length). Because of this, observations of the spur with the IUE have begun in late 1983 by Raymond. It is expected that UV spectra of two or three positions along the spur will provide a definitive test of our hypothesis explaining its structure. Thus far, one good spectrum of the spur has been obtained with the IUE, and others are planned for this summer.

In order to learn whether the gradient in Type I spectra away from the leading edge in this region of the Cygnus Loop can be attributed to a gradient in local driving pressure, telescope time on the KPNO 2.1m with the IIDS was granted to Dufour and Hester during 1983 July in order to obtain detailed spectra of several positions along two or three strips from the edge to the back end of visible optical emission (at points along some of the "slices" of HPD). From the spectra it was hoped to measure the temperatures (from [O III] and [N II]) and densities (or equivalently, pressures) (from [S II] and possibly [O II]) at several points at and behind the leading edge (and along the spur as well). Application of radiative shock wave theory should then enable us to calculate the thermal pressure in the cooling region at each position and examine the results for the presence of a gradient which would explain the observed trend in the emission line ratio variations.

Unfortunately, this run in 1983 July was largely clouded out, but currently Dufour is obtaining the necessary spectra with the 1.0m telescope at the better summer site of Lick Observatory. Our expectation, then, is to see the measured pressure decrease in a manner consistent with the changes in shock-velocity-sensitive line ratios already seen. It is quite possible that this will not be the result of these measurements, in which case it will be necessary to consider one or another of the other possibilities suggested in HPD. These include the possibility that shocks farther in and thus older have propagated on average farther into denser cloudlet interiors. The full explanation could be complicated, but looking for pressure differentials is an important clarifying step.

We also note that R. Fesen has unpublished spectra of several locations behind the leading edge of a region in the northwest part of the Cygnus Loop which overlaps with the second region for which we have interference filter photographs obtained by Dufour and Parker several years ago with the KPNO 0.91m telescope, and more recently, CCD imagery obtained by Hester at KPNO in 1983 August. We hope that it will ultimately be possible to combine our imagery data with his spectroscopy in order to perform an analysis similar to that described above for this second (morphologically dissimilar) region as well.

As noted previously, the gradient in the velocity-sensitive lines along the spur suggests a gradient in shock velocity along it, possibly due to a gradient in preshock density. The IUE spectra planned to be taken along the spur should immediately show whether or not this interpretation is fully consistent. If the UV lines are consistent, then the spur provides a unique opportunity -- an isolated linear feature along which nature displays a clean example of a complete shock wave plus cooling zone. Even better, the gradient in shock velocity displays the continuous variation of spectrum verses velocity -- a modeler's dream! In earlier work on this filament, HPD showed that the variations in line ratios along the spur had essentially the behavior expected from existing shock wave models (c. f. Figure 18 of their paper), but disagreed with the models on normalization. That is, ratio verses ratio diagrams representing individual pixels taken along the spur tracked model behavior, but were generally displaced by nearly constant factors that seemed explainable as deficiencies in the models. In order to further study the spur with improved photometric accuracy and higher spatial resolution, Dufour and Hester have applied for time on the KPNO 0.91m telescope with the CCD camera to obtain (hopefully) high quality photoelectric imagery of the spur through various interference filters. These new imagery data, coupled with the IIDS and IUE spectroscopy noted previously, should provide a data set of exceptional quality of a clean shock feature which could be used as a standard of comparison for the next generation of shock models (to be discussed later in this proposal).

It has already been noted that the field of the VLA radio map lies just north of the region studied by HPD. However, Einstein data exists for this area and we have also obtained some CCD imagery of this region through various interference filters with the KPNO 0.91m in 1983 August. Reduction of the data is nearly complet at the time of this writing. This should enable us to compare the optical and radio (and X-ray) structure of a region in the Cygnus

Loop for the first time at high spatial resolution (hopefully at the 1 - 2 arc second level).

3.3. EXTRAGALACTIC SNR SPECTRA

One of the PI's areas of interest is using the spectra of emission nebulae as diagnostics of the chemical composition of galaxies, from which fundamentally valuable information about the nucleosynthesis of the elements in stars and their effects on the chemical evolution of galaxies can be inferred. The utilization of SNRs for such purposes is still in its infancy, and only recently have such studies appeared in the literature. Notable are the studies of Binette et al. (1982) for galactic SNRs and those of Blair, Kirshner, and Chevalier (1982) and of Dennefeld and Kunth (1982) for SNRs in M31. These studies can be characterized by their use of the "old" theoretical models of Raymond (1979), Shull and McKee (1979), and/or Dopita (1977), (though Binette et al. note their use of updated but yet unpublished models by Dopita) coupled with some usage of empirical data on spectral relationships suggested by galactic SNRs (somewhat heavily weighted by the Cygnus Loop). In later sections of this proposal we will point out many of our concerns about these models and numerous improvements which can (and SHOULD) be made in order for them to better represent the physical situation in actual SNRs.

During the past few years Dufour's investigations of the spectra of H II regions in numerous metal-poor gassy irregular galaxies have stumbled across a number of SNRs in these systems, most notable in the Local Group irregulars IC 1613 and NGC 6822 (c.f. Talent 1981, and Killen and Dufour 1982, respectively). During the summer of 1983 John Raymond and Don Cox ran several versions of an upgraded SNR model code in an attempt to successfully model the optical spectra of these SNRs with realistic depleted abundance sets provided by Dufour based on the results of his recent studies of the abundances of He, C, N, O, Ne, Mg, Si, S, Cl, and Ar, relative to H, in the H II regions of galaxies which have a range of "metallicity" of $7.0 \leq 12+\log O/H \leq 8.0$.

Development of a series of "modernized" SNR models covering the spectrum of abundances observed in external galaxies will not only have great utility in interpreting the spectra of a variety of astrophysically interesting objects, but only recently has been made practical by the publication of several major studies of abundances in H II regions of external galaxies. Of particular note for these purposes is the study of Dufour, Shields, and Talbot (1983) of carbon abundances in the Magellanic Clouds and the Orion Nebula, which for the first time, gives us an idea of how the carbon abundance varies with the other elements cited above as a function of metallicity or chemical "age" of galaxies. In this study, Dufour et al. used IUE observations of the ultraviolet carbon lines to determine the carbon abundances. Currently, Dufour is analyzing high dispersion IUE data recently obtained of H II regions in the MWG, the Magellanic Clouds, and in several other galaxies, in order to derive the gaseous phase abundances of C, Si, and Mg in the ISM of these systems.

Since carbon is an important element affecting the UV/optical radiation field and cooling processes of shock waves in their radiative phases, we anticipate that Raymond's new models using the abundance sets supplied by Dufour will have great utility in future application of SNRs as diagnostics of the chemical composition of the ISM in external galaxies, most notably those with a sparse population of H II regions, such as the earlier types of spirals and some irregulars in which current star formation is relatively inactive (IC 1613 is a good example).

It is apparent that there is much to gain in the use of SNR spectra as abundance diagnostics, but such use at present is limited (outright dangerous!) by rather ancient nature of the models available. We hope to rectify this situation through the application and publication of a set of new models calculated for a range of shock velocities, preshock densities, and abundance sets using the upgraded model codes by Raymond and Cox described later in this proposal. The results of these models will be "tested" using published (and unpublished) data on SNRs in the MWG, LMC, SMC, NGC 6822, and IC 1613, which all have rather well determined abundances from UV/optical spectra of H II regions.

3.4. PRE-SUPERNOVA EJECTA FROM ETA CARINAE

A new area of SNR research which has produced extraordinarily exciting results recently concerns pockets of gas (called "condensations") apparently ejected only a few hundred years ago by the massive star Eta Carinae. Its surrounding gaseous medium offer an exceptional opportunity to study the physical situation of mass loss around an evolved, very massive star, possibly in an "immediate" pre-SN stage of evolution. Interest in this object and its remarkable situation has been increasing in recent years, largely due to Walborn and colleagues (c.f. Walborn and Liller 1977; and Walborn, Blanco, and Thackeray, 1978. for historical data, nomenclature, and references to previous studies).

Around the parent "star" and its compact "halo" (about 2 arc sec in diameter) is an irregular shell of condensations (the "homunculus", about 10 arc sec in diameter) apparently ejected from the central object during the 19th century (apparent time) and observed to be moving radially outward at velocities of about 500 km s^{-1}. Additionally, further out are several fainter condensations, apparently the result of previous ejections. Until recently, the physical properties and composition of these condensations were unknown. Last year, using IUE and photographic ground-based spectra, Davidson, Walborn, and Gull (1982) reported that the brightest, or "S" condensation, had a number of remarkable spectroscopic properties; including very strong nitrogen emission lines in five stage of ionization ranging from [N I] through N V, and the absence of the usually strong lines of [O I], [O II], [O III], C III], and C IV typical of the spectra of H II regions and planetary nebulae. Strong He II λ1640 in the IUE spectra (the strongest line in the UV) was also noted. Consequently, they concluded that the condensation was excessively rich in N and He, indicative of CNO-cycle processed material, ejected from the parent object. A situation comparable to that of the quasi-stationary flocculi in Cas A.

During the past two years, Dufour has been developing a collaboration with Davidson, Walborn, and Gull in the study of the detailed optical and UV spectra of the Eta Carinae condensations. The objectives can be summarized as: (1) understand the physical situation and nature of the shock phenomena in the condensations, and (2) derive the abundances of the astrophysically important elements (He, C, N, and O) in the condensations. As far back as 1971 July, Dufour has been acquiring moderate resolution spectra of the condensations and homunculus with the CTIO 4m and 1.5m telescopes. Recently, in 1984 March and April, he obtained high dispersion echelle spectra of the condensations with the 4m telescope at CTIO and with the IUE satellite from Goddard.

The echelle spectra show remarkable velocity structures in the condensations. All of the condensations show smooth broad "Wolf-Rayet" emission line profiles with dispersion velocities in the range of 600-800 km s^{-1}. However, the most remarkable features are "globules" or "sub-condensations", spatially coincident, but apparently moving radially outwards with velocities of upwards of 2000 km s^{-1} relative to the parent condensation. Such a situation is akin to that of material in some active galactic nuclei, such as Seyfert I galaxies, but never before seen on such a "small" scale. Therefore, understanding the physics and nature of the accelerating mechanisms of the material in the condensations may provide vital clues to the physical processes in active galaxies.

Much of the IUE and ground-based spectrophotometry of the largest, or "S", condensation have been reduced and combined with the hope of "nailing down" the physical situation and chemical composition of the "S" condensation. Unfortunately, the results have us more perplexed than ever! Basically the problem is that the IUE spectra suggest an entirely different picture than the ground-based spectra. The IUE spectra show lines of N III], N IV], N V, and He II indicative of a blast-wave-like shocked medium, while the ground-based spectra are more indicative of a photoionized medium (albeit N-rich) with Te $\approx$ 13,500 °K (from [N II]) and Ne $\approx$ 3000 cm^{-3} (from [S II]). If we tie the ground-based data to the UV by absolute flux (including data from CCD imagery obtained by Davidson in 1982 with the CTIO 4m), then the λ1640 He II line is several times too strong compared to the λ4686 H II line (based on an expected $\lambda\lambda$1640/4686 ratio of about 7 from theory) observed in the ground-based spectra (despite numerous attempts to reconcile the discrepancy by envoking peculiar extinction laws and plausible aperture corrections).

The spectrophotometry data for the S condensation has been reduced and analyzed as best as possible using "traditional" nebular diagnostic techniques, and a paper is being prepared for submission to the Astrophysical Journal. Another paper on the kinematical properties is planned to be completed by late 1984. In addition, model calculations of the condensations are being considered in conjunction with John Raymond at CFA and/or Bill Mathews at Lick Observatory.

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