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Final Report for NASA Grant *NSG-5248*

Observations of Interstellar Lines using the IUE Satellite

Covering the Years 1978 - 1988

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1. Overview

NASA Grant NSG-5248 to Princeton University supported astronomical research for Dr. Edward B. Jenkins, who used the *IUE* Satellite to perform 4 principal observing projects with various collaborators over the period 1978 to 1988. While the projects addressed very different astrophysical topics, they all had one trait in common, namely, the study of absorption lines produced by dispersed gases in front of various sources in the sky. Summarized below are the 4 projects, the approximate time periods of each, and collaborators (if any):

[1] *Interstellar Absorption Lines in High Latitude Stars* 1978 - 1980.

[2] *Shocked Gas Associated with the Vela and Monoceros Supernova Remnants* 1981 - 1983. Collaborators: G. Wallerstein, Univ. of Washington, J. I. Silk, Univ. of California, Berkeley.

[3] *Lyman Alpha Halos of Galaxies* 1983 - 1986. This program evolved into one called "*Intergalactic Lyman-α Systems*" during the later portion of the period. Collaborators: D. G. York and A. Caulet, University of Chicago, C. C. Wu, Computer Sciences Corp., J. C. Blades, StSci, and D. C. Morton, Anglo-Australian Telescope and Herzberg Inst.

[4] *Abundances and Depletions in Dense Diffuse Clouds* 1986 - 1987. This project was carried out at Princeton entirely by Dr. Charles L. Joseph, who collaborated with T. P. Snow at the Univ. of Colorado.

In addition to the above formal programs, the grant supported several impromptu research projects which did not involve the use of *IUE* observing time explicitly awarded to the Principal Investigator.

2. Research Results

2.1. Interstellar Absorption Lines in High Latitude Stars

The purpose of this observing program was to analyze the interstellar lines appearing in stars at large distances from the galactic plane. At the time, most analyses of interstellar lines had been accomplished for data recorded by the *Copernicus* satellite. However, *Copernicus* was not able to observe stars with a visual magnitude fainter than about 6. Since most of the distant, high latitude stars are fainter than this limit, *IUE* was employed to observe these objects and provide information on the composition, physical state and dynamics of the gas at high *z*.

Shortly after the observations were taken, the data were subjected to intensive reduction and measurements. After expending considerable effort on the program and at about the time the research was evolving into the interpretative stage, the investigator (E. Jenkins) was informed by the *IUE* project that the photometric quality of the spectra had been compromised by the use of a defective Intensity Transfer Function (ITF) during initial processing by the project. Some time later, the IUE project obtained a valid ITF and then furnished new scans for the observations. At this point, all steps of the investigation had to be repeated. The psychological setback of having to work on same data for a second time and the demands of other research programs which materialized at later times had a significant adverse effect on the momentum of the research. As a consequence, a few of the general conclusions did not evolve until after other investigators had a chance to work on the data as they became available in the archives after the expiration of the proprietary period. For instance, the Princeton effort was scooped on the discussion of the existence of Si IV and C IV at high *z* by Pettini and West (1982).

In spite of the troubles precipitated by the ITF error, interesting conclusions on the abundances of certain heavy elements away from the plane of the galaxy did evolve from the program. An initial report of the results by Jenkins (1983) was followed by a more definitive exposition after he had used extra data in the archives derived from other programs (Jenkins

1986). In short, Jenkins found that the patterns of element depletions in high z gas differed from material found in the plane. In particular, the ratio of Fe II to S II increased markedly for z distances greater than a few hundred pc.

2.2. Shocked Gas Associated with the Vela Supernova Remnant

Absorption line studies of shocked material in the Vela Supernova Remnant began in the visible with the Ca II and Na I observations by Wallerstein and Silk (1971). These initial findings were supplemented by the rich array of important lines observed by the *Copernicus* satellite (Jenkins, Silk and Wallerstein 1976a,b). While the *Copernicus* results provided important information on the abundances and ionization of many elements in high-velocity clumps of gas, the number of stars which could be sampled was limited, since the *Copernicus* spectrometer did not have the enormous spectral multiplexing capability of *IUE*. To obtain a much better global impression of the dynamics and extent of the Vela Remnant, we recorded uv spectra of 45 stars behind, in front of (as a control), or very near the remnant.

The survey took two years to complete. However after the first year we were rewarded by an interesting surprise. The fine-structure excitation of the neutral carbon in front of one star, HD 72350, proved to be extraordinarily large. As a result, we inferred that a foreground cloud was at an unusually high pressure, probably as a result of being subjected to the blast wave in the intercloud medium. This interpretation and the data for HD 72350 were presented in a paper by Jenkins, Silk, Wallerstein and Leep (1981). Somewhat later, we presented the conclusions for all of the stars behind the Vela Remnant (Jenkins, Wallerstein and Silk 1984). In this paper, we showed that one other star, HD 72648, also showed evidence of a recently shocked, overpressured cloud. For the entire survey, we found that about one-third of the stars showed components of material at large velocities -- again evidence for the interactions caused by the blast wave. To our surprise, however, we found that the motions were generally chaotic, rather than anything resembling an outward expansion. An interesting theoretical interpretation of this effect has been presented by Meaburn, Hartquist and Dyson (1988).

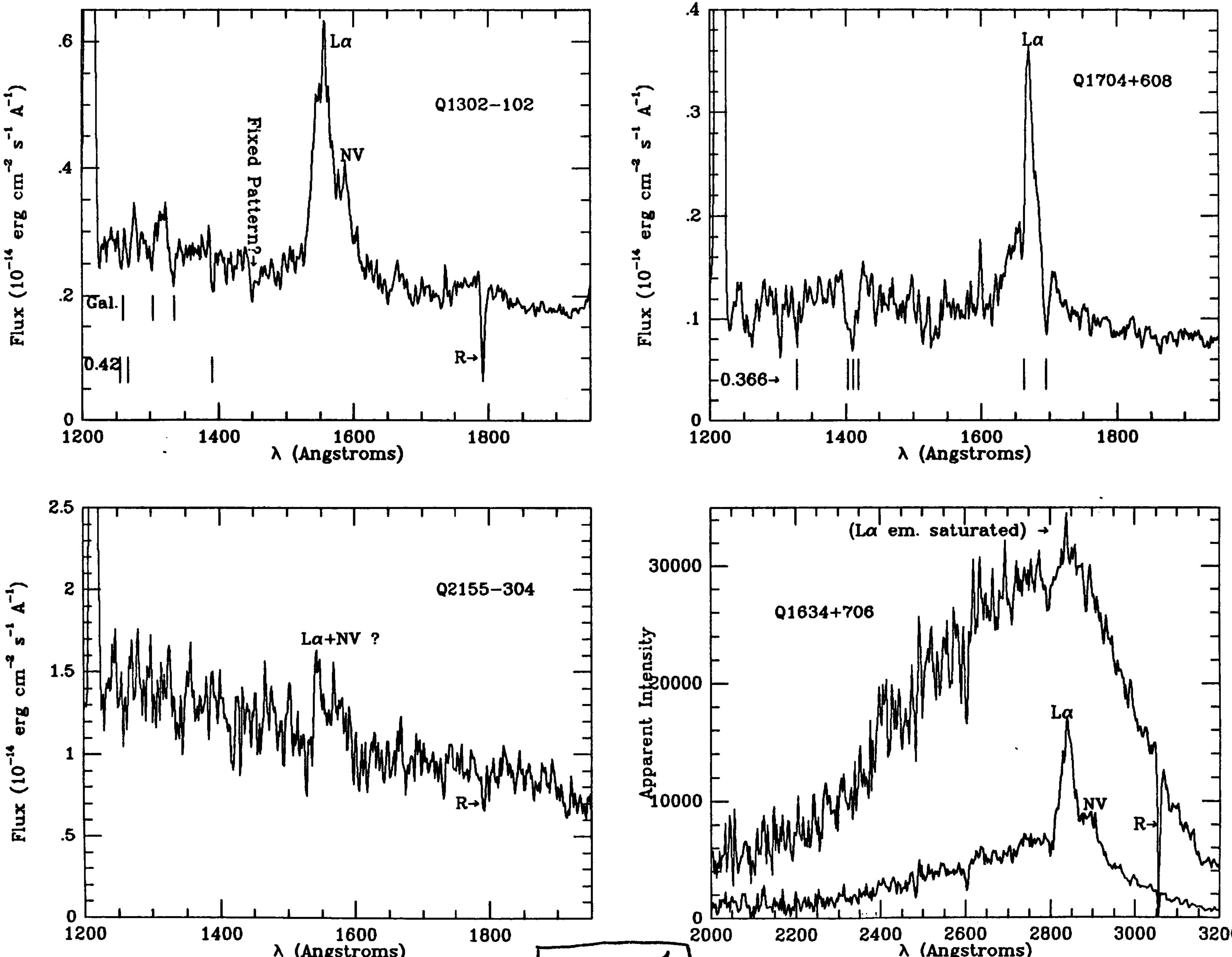
They explained our results as the manifestation of fragmenting "blisters" created by non-linear growths of Rayleigh-Taylor, thermal, and other instabilities.

2.3. Lyman-α Halos of Galaxies and Intergalactic Lyman-α Systems

It has long been known from work at visible wavelengths that distant QSOs exhibit multiple absorption line systems at redshifts z(abs) $<$ z(QSO em.). While indirect conclusions about the nature of the intervening systems could be derived from their statistical properties, there are few direct observational links between the QSO absorption lines and structures which have been identified by other means, such as the outer portions of *known* galaxies. Evidence from 21-cm mappings of certain galaxies show that gaseous matter extends well beyond the visible portions of such systems. Our objective with *IUE* was to ascertain whether extensions of such gas create uv absorption lines similar to those seen at greater redshifts in the visible. Except for the lines of Ca II and Mg II, galaxies which are close enough to be seen have redshifts which are small enough to keep the strongest and most interesting resonance transitions in the ultraviolet.

The objective of our *IUE* observing program was to look at the small number of relatively bright QSOs which are not far from galaxies in projection. Our second goal was to determine the number of L-α absorption lines in the redshift range 0.1 - 1.0 for comparison with the numbers found from ground-based studies at high redshift ($2 < z < 3.5$). Our aim here was to resolve any possible evolution in the number and character of L-α clouds at different epochs.

Figure 1 shows the results of special reductions of our data. Except for the lower right panel (for Q1634+706), we combined several exposures after invoking special processing to remove broad sensitivity variations and cosmic-ray hits. As is clear from the figures, absorption lines can be discerned, and we arrived at the following conclusions:



Q1302−102
Lα
NV
Fixed Pattern?→
Gal.
0.42
R→
Flux (10^{-14} erg cm^{-2} s^{-1} A^{-1})
λ (Angstroms)
Q1704+608
Lα
0.366→
Flux (10^{-14} erg cm^{-2} s^{-1} A^{-1})
λ (Angstroms)
Q2155−304
Lα+NV ?
R→
Flux (10^{-14} erg cm^{-2} s^{-1} A^{-1})
λ (Angstroms)
Q1634+706
(Lα em. saturated) →
Lα
NV
R→
Apparent Intensity
λ (Angstroms)

Figure 1

Q1302-102:

The strongest absorption complexes, those near 1260, 1304 and 1335Å, can be seen at $z = 0$, corresponding to absorption in our galaxy (labeled "Gal." in the figure). In addition, there might be an absorption system at $z = 0.042$. No lines at $z = 0.001$, 0.094 or 0.145 from the outskirts of 3 known galaxies in projection can be identified with much confidence, although some of the expected lines coincide with lines identified in the figure. (For example, C II absorption at 1335Å from our galaxy overlaps the expected position of L-α for $z = 0.094$; likewise, this same C II line for $z = 0.042$ could coincide with the L-α line at $z = 0.145$.)

Q1704+608:

There is good evidence that an intervening cloud of highly ionized gas at $z = 0.366$ is in front of this QSO whose L-α and NV emission lines are at $z = 0.374$. Strong absorptions at 1515 and 1531Å may be from systems showing only L-α lines.

Q2155-304:

This BL Lac type object shows a flux enhancement between 1540 and 1570Å, which might be from L-α and NV emission at $z = 0.268$. If this z is correct, it is intriguing to note that the variance of the continuum shortward of the emission peak is larger than that at longer wavelengths. Presently, we can not rule out the possibility that the effect is purely instrumental in nature, but there is a hint that a L-α forest at low z may be the explanation.

Q1634+706

This is the only object we have observed intensively to look for a L-α forest at $z \sim 1.0$. The apparent difference in the continuum variance on either side of the L-α emission peak at 2840Å disappears after more careful processing and rectification to a flat continuum. A short paper giving a count of L-α systems to a modest equivalent width limit was presented at a conference on QSO absorption lines (Jenkins, et al. 1987).

It is clear that the IUE observations are of some use in registering the presence of intergalactic gas, even at low resolution. To our surprise, however, we found no conclusive evidence that the outskirts of galaxies produce conspicuous absorption line systems -- at least at the projected distances of a few hundred kpc from the centers. Our goal of detecting the L-α absorptions from these galactic extensions was badly compromised by unforseen photometric anomalies caused by beam pulling from the strong geocoronal L-α emission peak. A paper is currently being prepared for the *Astrophysical Journal* which discusses our findings.

2.4. Abundances and Depletions in Dense Diffuse Clouds

C. Joseph and T. Snow are completing a successful multi-year study of the interstellar medium. This study has produced 2 papers: Joseph *et al.* (1986) and Joseph (1989, PASP submitted). Two additional Ap.J. papers from this research are expected to be submitted in 1989, with the cost being supported from an ongoing *IUE* grant to T. Snow.

The main emphasis of this program has been to study the abundances and depletions in lines of sight through the outer edges of dense molecular clouds and to correlate differences in the element-to-element abundances with differences in the peculiar UV selective extinction curve. Understanding the selective extinction of star light not only provides important constraints for interstellar grain models, but it is crucial for researchers attempting to determine the intrinsic luminosity of hot stars situated be behind clouds containing dust. In addition, UV-determined depletions in a number of dense molecular clouds have been measured for the first time (Joseph *et al.* 1986), providing constraints on the chemical makeup of the grains in these environments.

This type of research is observationally intensive because high-quality data are required for these UV-faint stars. Multiple images (10 for each camera) are typically needed to be coadded to improve the signal-to-noise ratio. This requirement has limited the number of sightlines that can be evaluated each year to 3 or less. The large amount of data collected on single line of sight, however, has proved beneficial for studies of the IUE detector. In a parallel effort, a paper (Joseph 1989) has been submitted to the Publication of the Astronomical Society of the Pacific (P.A.S.P.), which emphasizes some potential dangers of using a single IUE image to determine interstellar column densities.

Abundances have been examined for 11 stars and significant (0.5 to 1.0 dex) variations are found, leading to new important empirical relationships. For example, Mn II/Fe II abundance ratios appear to be small (0.5 dex less than in diffuse clouds) in lines of sight exhibiting a shallow (about 1.0 dex less than normal) 2200 Å extinction bump. In the optical, the CN/Fe I abundance ratio appears to be large only for those lines of sight with a shallow 2200 Å bumps (Joseph, Snow, and Seab 1989. Sightlines through other dense clouds have element-to-element abundances and extinction properties similar to those found in the diffuse interstellar medium. One other paper (Joseph and Snow 1989) is nearly complete. A statistical technique is employed and the feasibility of using the IUE to measure Si I and Fe I is demonstrated. Element-to-element depletion ratios inferred from the abundances of neutral atoms in the cloud cores confirm the existence of two different types of dense clouds. An additional paper, which should be submitted in 1989, will review all results obtained to date.

2.5. Ancillary Studies and Papers Supported by the Grant

For the first of many symposia which discussed results from *IUE*, Jenkins gave an invited review paper on the new insights the observations had brought forth on the interstellar medium. The main emphasis of this paper (Jenkins 1981) was on the interpretation of the Si IV and C IV lines.

M. Voit, who at the time was a Princeton undergraduate, measured the C I absorption lines toward a large number of objects whose spectra were taken from the archives. Mr. Voit performed this work for his Senior Thesis topic. The objective of this project was to see if different classes of target stars had measurable differences in the relative populations of C I in excited fine structure states for their foreground gaseous material. Voit's work clearly showed that stars behind the Vela and Monoceros supernova remnants had elevated populations of excited C I, indicating that the gases were at high pressures, when compared to a control set of stars located in random portions of the sky. He also attempted to measure differences between stars located in associations and single stars well removed from other stars of early spectral type. A slight elevation in pressure was seen for the stars in associations, but the difference was not significant.

An important aspect of Voit's research on C I made use of a method of consolidating noisy measurements of equivalent widths for large numbers of stars. A validation of the correctness of the procedure was carried out by Jenkins, who developed a generalized mathematical description of the analysis technique in a variety of applications (Jenkins 1986b). A simplified discussion of how to apply the method to *IUE* observations of very weak lines for many stars to obtain global abundances was presented later by Jenkins (1988).

An outgrowth of the research described in §**2.3** above was the creation of a line list for identifying absorption systems in QSOs. Since this list seemed to be of general value to other researchers, it was published in a paper appearing in the *Astrophysical Journal Supplements* (Morton, York and Jenkins 1988).

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