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Final Report
NASA IUE grant NAG5-797
The Winds of High Luminosity Late-type Bright Stars

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Report covering the period 1986 June 15 thru 1989 June 14

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Final Report, NAG5-797, Covering 6/15/86 – 6/14/89
Principal Investigators: Dr. R.E.Stencel and Dr. K.G.Carpenter, University of Colorado at Boulder
Note that Dr. Carpenter was P.I. until he left U of Colorado in Sept. 1988 for a Civil Service position at NASA Goddard.

IUE Guest Observer Approved Projects:
MGIKC: The Winds of High Luminosity K and M Stars.
MGJKC: Variations in the Chromosphere and Stellar Wind of Gamma Crucis.

1. Objectives –

The winds of high luminosity K and M stars likely play a major role in stellar evolution, yet this region of the H-R diagram is one of the least-studied with IUE, due to the very limited number of targets that are bright in the ultraviolet. However, high-resolution spectra of the long wavelength region of the few well-observed stars reveal extremely interesting spectra containing dozens of broad, frequently self-reversed and asymmetric Fe II emission lines in addition to the Mg II, Al II, and C II lines seen in all late-type stars. We proposed a comprehensive study of a sample of 13 such stars using both archive and new observations.

We studied the occurrence and characteristics of the Fe II line asymmetries to determine the radial dependence of the wind velocity for each star. We also investigated the dependence of the Fe II profiles on spectral type and luminosity class and thus the variation of the velocity fields with stellar type. This will allow us to judge the generality of the results reported for α Ori by Carpenter (1984b). In addition, we used new atomic data along with observations of the C II (UV 0.01) multiplet to estimate N_e in the stellar winds. Measures of relative Fe II fluxes can be used in a probability-of-escape model to determine the opacity and hydrogen column density versus height in the chromosphere of each star. Finally, analysis of the fluorescent Fe II lines (pumped by Lyα) near 2507 Å will yield estimates of the intrinsic stellar Lyα flux that cannot be measured directly because of interstellar and circumstellar absorption.

One important goal of the effort was to acquire high resolution spectra of the whole 2300-3200 Å region of 13 luminous K and M stars as a data base that will be enormously valuable in planning observations with the Hubble Space Telescope High Resolution Spectrograph, which will be able to observe only small portions of the spectrum at one time with high sensitivity.

We also proposed to follow up the recent discovery of significant variations in the Fe II chromospheric emission line profiles from the M-giant Gamma Cru for the purpose of determining the underlying cause of the variations. The star was observed at five different times during the year with SWP low resolution and LWPHI and LWPLO resolution to determine whether the apparent increase in the opacity of the stellar wind and chromosphere is: 1) due to additional mass being added to the outer atmosphere through a one-time ejection of mass or an increase in the mass loss rate, or 2) due to a temporary or permanent increase in the chromospheric heating rate, or 3) is a periodic effect due, for example, to rotation and the resulting variable visibility of inhomogeneities in the chromosphere. This star is the first single, non-Mira M-giant for which there is clear evidence from UV lines of substantial chromospheric variation.

2. Data Obtained -

MGIKC: 8US1 shifts, plus additional 1US1 and 2US2 shifts as part of program MGJKC, as well as archival data.

3. Analyses and results -

a. γ Cru reference spectrum

A guide to the ultraviolet spectrum of M-type giants and supergiants, whose outer atmospheres contain warm chromospheres but not coronae, was developed for use in planning high resolution observations with the Hubble Space Telescope and as an aid in the analysis of data already acquired with the *International Ultraviolet Explorer* satellite. The details of the Fe II-rich spectrum presented here may also be useful in studies of a wide variety of other astronomical objects with Fe II emission spectra such as Be stars, novae, quasars, and the nuclei of active galaxies.

We took the M3 giant Gamma Crucis as the archetype of the cooler, oxygen-rich, non-coronal stars and present line identifications and integrated line flux measurements of the chromospheric emission features seen in the

1200 - 3200 Å range of IUE high resolution spectra. In addition, we identified a set of absorption features toward the longer wavelength end of this range which can be used to characterize the radial velocity of the stellar photosphere.

We summarized all known fluorescence processes operating in the outer atmosphere of Gamma Crucis and present the discovery of 8 previously unknown pumping processes and 21 new fluorescent line products. These processes are active in the outer atmospheres of most other non-coronal giant and supergiant stars as well.

Two of the new fluorescence processes, involving new energy levels recently found in laboratory analysis of Cr II and Fe II, explain emission features seen at 1347 and 1360 Å. The 1347 Å feature coincides with a Cr II line, which has a second transition within the profile of hydrogen Lyman alpha, allowing a selective photoexcitation of its upper level. The presence of Cr II in Gamma Crucis is confirmed by a number of lines in the long wavelength region of the spectrum. The line at 1360 Å has earlier been identified as Fe II in spectra of cool stars and in the solar spectrum, but was assigned to two different transitions, predicted to be very close in wavelength to the observed stellar line. We suggest a third Fe II transition, involving a newly identified Fe II level at 13.0 eV, which is predicted to have three observable lines in the UV region. One of these lines falls very close to hydrogen Lyman alpha, the second one on the right wing of H Lyman alpha and the third line at 1360.17 Å. Other fine-structure levels of the same upper term as the new level have also been found and they show the same decay pattern.

Six of the new processes, which lead to the production of 10 fluorescent features, involve known energy levels which were not previously recognized as populated by selective radiative excitation. Four of these are examples of self-fluorescence, in which one or more lines of Fe II populate selected other levels in Fe II by photo-excitation of coincident lines. Two of these self-fluorescence processes include two distinct pumps of the same upper level, while two are powered by single pumps. These four processes produce a total of eight lines in Gamma Cru: 1) two separate lines of Fe II UV 1 and UV 3 independently pump the same upper level of Fe II (through lines of UV 203 and 165) to produce lines near 2435 and 2741 Å, 2) the Fe II (UV 1) line near 2599 pumps a UV 265 line to produce lines of UV 207 near 2498 and 2493 Å, 3) three lines from multiplets UV33, UV 207, and UV 63 pump

UV 161 and UV 198 lines at 2493 and 2769 Å to produce a UV 161 line at 2482 Å, and 4) the UV 1 line at 2631 Å pumps a UV 171 line to produce lines from UV 158 and UV 171 at 2539, 2549, and 2619 Å. Ni II (UV 20) has long been suggested as an identification for the feature at 2416 Å, but its source of excitation was unknown. We propose that the upper level of that transition is radiatively excited by the Si II (UV 0.01) lines at 2334.4 and 2334.6 Å pumping the Ni II (UV 20) line at 2334.6 Å. The fluorescence processes in these stars can become very complicated, as illustrated by our identification of the 2516 Å feature as a Si I (UV 1) line from an upper level populated by the Fe II line near 2507 Å pumping a coincident Si I line. The Fe II line is itself a well-known fluorescent feature produced by Lyman alpha pumping, so that indirectly, the Si feature is also produced and controlled by hydrogen Lyman alpha!

We have identified nine features as newly recognized decays from levels already known to be populated by radiative pumping. The feature at 2356 Å is now identified with the Fe I (UV 12) line which originates from the upper level populated by the Mg II k-line pumping of a coincident Fe I UV 44 line. This pump is known for its production of the very bright and well-known fluorescent Fe I UV 44 features near 2823 and 2844 Å. The feature at 2537 Å is identified with a line of Fe II (UV 363), produced by secondary cascade from levels previously known to be populated by the ever-present hydrogen Lyman alpha pump. Seven new direct decays from high-energy levels of Fe II photo-excited by Lyman alpha, producing lines near 1369, 2415, 2457.1, 2430, 2438, 2448, and 2457.0 Å have also been identified.

The enhancement of selected line strengths by "line leakage" is discussed. This process occurs when a very high opacity line shares a common upper level with a much lower probability transition, such as an intersystem line. The line with the lower transition probability is enhanced since it provides the only route out of a series of endless scatterings in the stronger line. We indicate the lines in the Gamma Cru spectrum most strongly affected by this process.

Finally, we intend to discuss the generality of our results for Gamma Cru and their applicability to the spectra of non-coronal stars with different effective temperatures and gravities. This analysis is in progress and should lead to one or more reports in due course. Attached are lists of spectra examined and sample tables of preliminary results.

b. Fluorescence and Fe II studies

Fluorescence processes active in the outer atmospheres of non-coronal cool stars and the UV lines they produce are summarized. Eight new pumping processes and 21 new fluorescent line products are discussed. The new processes, which produce 12 lines, involve energy levels not previously known to be radiatively populated. Four of these are examples of self-fluorescence, whereby one or more lines of Fe II photo-excite through coincident lines the upper levels of other Fe II lines seen in emission, while two others explain the selective excitation of solitary Ni II and Si I lines. Nine of the line products are newly recognized decays from levels in Fe I and Fe II already known to be radiatively populated.

PUBLICATIONS CITING SUPPORT OF NAG5-797:

1. "The UV Spectrum of Non-Coronal Late-type Stars: The Gamma Crucis (M3.4 III) Reference Spectrum.", K.Carpenter, J.Pesce, R.Stencel, A.Brown, S.Johansson and R.Wing, 1989, *Astrophys. Journal* **68**, 345.

2. "New Fluorescence Processes and Line Identifications in the UV Spectra of Cool Stars", K.Carpenter and S.Johansson, 1988 in *A Decade of UV Astronomy with the IUE Satellite*, ESA Spec. Publ. 281, p. 349.

3. "Identification of New Fluorescence Processes in the UV Spectra of Cool Stars from New Energy Levels of Fe II and Cr II", S.Johansson and K.Carpenter, 1988 in *A Decade of UV Astronomy with the IUE Satellite*, ESA Spec. Publ. 281, p. 361.

4. "Fluorescence in the Outer Atmospheres of Red Giant Stars", K.Carpenter, 1989 in *The Evolution of Peculiar Red Giant Stars: IAU Colloquium 106*, eds. H. Johnson and B. Zuckerman, in press.

PAPERS IN PREPARATION:

1. "The UV Spectrum of Non-Coronal Late-type Stars: Luminosity Dependent Differences in the Outer Atmospheres of Red Giants", D.Neff, K.Carpenter and R.Stencel 1989 in preparation.

JUN 27 1989

STAR	IMAGE #	EXPO TIME (min.)	LONGVEC NAME	HIPLOTS CREATED ? MARKED?	MEAS. STATUS
π Pup	LWP 8334	120	PIPUP.LV	√	
K3Ib	LWP 8335	WAVECAL			
β Ara	LWP 6909	90	BARA.LV	√	
K3Ib-IIa					
ξ Cyg	LWR 3183	6	XICYG6.LV	√	
K4/5Ib-II	LWR 4716	90	XICYG90.LV	√	
ψ^1 Aur	LWP 9110	150	PSIAUR150.LV	√	
K5-M0Iab	LWP 9117	370	PSIAUR370.LV	√	
	LWP 9111	WAVECAL			
	LWR 10498	45	PSIAUR45.LV	√	
	LWP 9118	WAVECAL			
σ CMa	LWP 8325	6.5	SIGCMA6_5.LV	√	
K7Ib	LWP 9969	20	SIGCMA20.LV	√	
	LWP 5762	75	SIGCMA75.LV	√√	JEP
	LWP 9970	105	SIGCMA105.LV	√	
	LWP 3264	280	SIGCMA280.LV	√√	KH
	LWP 3265	WAVECAL			
α Ori	LWR 9600	30	AORI30.LV	√	
M1/2Ia/ab	LWR 1371	120	AORI120.LV		
μ Cep	LWP 8306	390	MUCEP.LV	√	
M2Iab	LWP 8307	WAVECAL			
119 Tau	LWR 2946	60 ?	SPATIAL		
M2Ia-Ib	LWR 8952	60	TAU60.LV	√	
	LWR 8453	?	SPATIAL		
	LWP 9472	45	TAU45.LV	√	
	LWP 9455	370	TAU370.LV	√	
	LWP 9456	WAVECAL			
	LWP 7626	800	TAU800.LV	√√	KH
	LWP 7627	WAVECAL			
β Peg	LWP 3775	5	BPEG5.LV	√√	DHN
M2II-III	LWR 4693	120	BPEG120.LV	√√	DHN
	LWR 8750	200	BPEG200.LV	√√	DHN
	LWP 4571	335	BPEG335.LV	√√	DHN
	LWP 4572	WAVECAL			
	LWR 10804	40	BPEG40.LV	√√	DHN

STAR	IMAGE #	EXPO TIME (min.)	LONGVEC NAME	HIPLOTS CREATED ? MARKED?	MEAS. STATUS
π Aur	LWP 9471	30	PIAUR30.LV	√√	DHN
M3II	LWP 9470	130	PIAUR130.LV	√√	DHN
	LWP 9409	375	PIAUR375.LV	√√	DHN
	LWP 9410	WAVECAL			
ρ Per	LWR 7144	25	RHO_PER25.LV	√√	
M4II	LWP 6559	10	RHO_PER10.LV	√√	
	LWP 9112	100	RHO_PER100.LV	√√	
	LWP 9113	WAVECAL			
	LWP 6553	330	RHO_PER330.LV	√√	
η Per	LWR 7558	21	ETAPER21.LV	√	
M3Ib-IIa	LWP 9473	25	ETAPER25.LV	√	
	LWP 10243	190	SPATIAL		
	LWP 7024	350	ETAPER350.LV	√√	KH/DHN
	LWP 7025	WAVECAL			
λ Vel	LWP 8331	7.5	LVEL7_5.LV	√	
K4Ib-II	LWR 3208	20	LVEL20.LV	√	
	LWR 4705	7.5	SPATIAL		
	LWP 8332	100	LVEL100.LV	√√	KH
	LWP 8333	WAVECAL			
	LWR 13536	270	LVEL270.LV	√	

*NOTE: MEASURES BY OTHER THAN "DHN" ARE LESS RELIABLE