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Edited by Hugo van Woerden

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TOPICS IN INTERSTELLAR MATTER

INVITED REVIEWS GIVEN FOR COMMISSION 34 (INTERSTELLAR MATTER) OF THE INTERNATIONAL ASTRONOMICAL UNION, AT THE SIXTEENTH GENERAL ASSEMBLY OF IAU, GRENOBLE, AUGUST 1976

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FOREWORD

Interstellar matter is one of the most active fields of research in present-day astronomy. Observational information spans the full electromagnetic spectrum from gamma rays through rocket-ultraviolet, optical, infrared and millimeter to long radio waves. Results of research in physical chemistry find as much application as mathematical methods. Interstellar matter plays a leading role in studies of our Galaxy and of external galaxies, and contributes increasingly to stellar astronomy.

At the 16th General Assembly of the International Astronomical Union, held in August 1976 in Grenoble, France, the many new developments in this vast field were surveyed in a number of sessions of Commission 34 (Interstellar Matter), mostly jointly with other Commissions of the Union. Separate sessions were devoted to: The hot interstellar gas phase, Interaction of stars and interstellar medium, Interstellar molecules and dust, The large-scale distribution of interstellar matter in the Galaxy, and Interstellar matter in external galaxies. Twenty-four invited review papers were presented and discussed in these sessions.

The quality and success of these topical reviews made it seem desirable to make them available to a wider audience. Professor Edith Müller, the new General Secretary of the IAU, enthusiastically supported the idea. Most importantly, the reviewers - who had originally been promised that an oral paper was the only requirement - agreed to prepare written versions. I am grateful to Mrs. Müller, to the authors, and to Reidel Publishing for their collaboration in the preparation of this book.

I further wish to thank the Organizing Committee of Commission 34 (Drs. J.E. Baldwin, F.D. Kahn, G.S. Khromov, B. Lynds, T.K. Menon, D.C. Morton, M. Peimbert and B.J. Robinson) and especially its Vice-President, Dr. George B. Field, for their share in the preparation of the meetings. Equally, I am grateful to the (Vice-)Presidents of Commissions 28, 33, 40 and 44: E.B. Holmberg, L. Perek and F.J. Kerr, N. Parijskij and A.D. Code for their cooperation. Special thanks go to Dr. E.B. Jenkins, who organized the Hot-Gas session and edited its Proceedings. Important suggestions also came from several commission members, especially Dr. W.B. Burton.

The sessions were prepared while I was on leave from Groningen at the Division of Radiophysics, CSIRO, Sydney in 1975/76. I wish to thank Drs. J.P. Wild and B.J. Robinson for their hospitality, and the office staff for their efficient help. Mrs. Joan Jones, in particular, through her tireless efforts at most improbable hours, ensured the timely preparation of the meetings.

Finally, and above all, I wish to thank the Groningen secretaries, Joke Nunnink, Ina Cameron and Roelie Olde, for their dedicated help. They retyped almost half of the manuscripts, and made them really "camera-ready". The final shape of the book is very largely their making.

Hugo van Woerden
Editor

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THE HOT INTERSTELLAR GAS PHASE

Papers presented in a joint session of IAU Commissions 44 (Space Research) and 34 (Interstellar Matter), Grenoble, 25 August 1976.

Session Chairman: George B. Field

Chapter Editor: Edward B. Jenkins

INTRODUCTION

E.B. Jenkins

One measure of progress in research on interstellar matter is our expanded awareness of the broad variations in the physical state of material dispersed throughout our galaxy. As they become recognized, the various regimes of density, temperature and ionization are often characterized as discrete "phases," although in some circumstances the boundaries between such phases may not be as well defined as we once thought. At one end of the spectrum of conditions are the compact gas clouds, rich in dust grains and complex molecules, having temperatures below a few tens of degrees K and densities in excess of 10^{-19} g cm^{-3}. If we exclude suprathermal particles (cosmic rays), we may identify the other extreme as collisionally ionized gas with a temperature on the order of 10^5 to 10^7 K and a mean density of around 10^{-27} g cm^{-3}.

Our perspective on the existence of a very hot phase of interstellar material, similar to that in the corona of our sun, may be traced back to a proposal by Spitzer in 1956 (Astrophys. J. 124, 20), who outlined indirect evidence for the presence of this gas and showed that such material is relatively immune to dissipation by conductive or radiative cooling. After a period of dormancy, the viewpoint that coronal gas may be an important constituent of interstellar material was reactivated by a recent surge of theoretical inquiry on origin and maintenance of the gas, coupled with the advent of new observational data which directly confirm its existence in space. The four articles in this section of the volume, two of them observational and two theoretical, outline some recent conclusions on the properties of the coronal gas and its evolution.

Hugo van Woerden (ed.), Topics in Interstellar Matter, 3.

OBSERVATIONS OF O VI

Edward B. Jenkins
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ABSTRACT

A useful spectroscopic tracer for a hot phase of interstellar gas is the O VI ion, which reaches its maximum concentration in collisional ionization between 10^5 and 10^6 K. Presently, over 70 stars have been observed for O VI absorption by the *Copernicus* satellite. Nearly all of the stars show broad, weak lines, but no evidence favoring a circumstellar origin for the gas can be found. An overall average for n_e of the hot gas in the galactic plane is of order 10^{-3} cm^{-3}. The relative volume in space occupied by the hot gas regions (and hence their internal density) is uncertain, but a filling factor in the range 0.02 to 0.2 seems most plausible. Fluctuations in radial velocities and column densities suggest there are roughly 6 regions per kpc, each with N(O VI) $\approx 10^{13}$ cm^{-2}. The observed rms dispersion of radial velocities for these regions is 26 km s^{-1}.

1. INTRODUCTION

A prime objective for the ultraviolet spectrometer aboard the *Copernicus* satellite has been to exploit a spectral region containing resonance lines of interstellar atoms in a variety of ionization stages. As expected, the stellar spectra yielded a rich array of narrow atomic lines, and also many from H_2, from which we have distilled information on the abundances, temperatures, excitation and distribution of the dominant, low-temperature phase of interstellar gas (Spitzer and Jenkins, 1975). Somewhat unanticipated, however, was the discovery of broad, shallow absorptions by O VI (Rogerson, York *et al*., 1973). This lithium-like ion has a strong resonance doublet at 1032 and 1038 Å which is observed in absorption toward a large fraction of the O and B stars studied with the satellite.

We can easily dismiss the notion that the O VI absorption features are attributable to cosmic-ray or X-ray ionization of cool gas clouds. The profile widths are always significantly broader than those from

Hugo van Woerden (ed.), Topics in Interstellar Matter, 5-16.

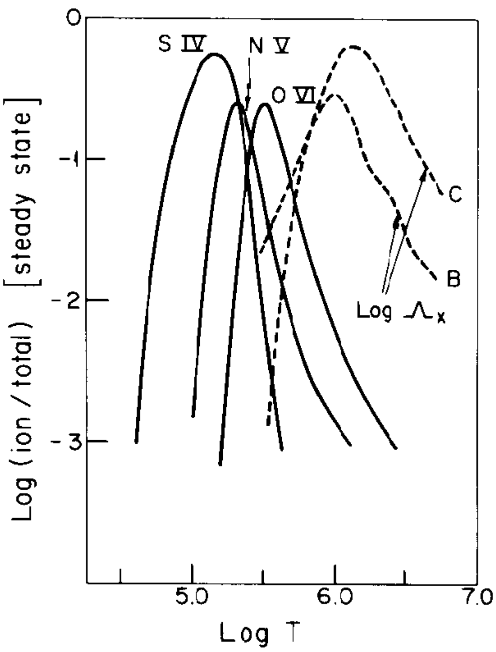

Fig. 1. Relative concentration, as a function of temperature, of coronal ions whose absorption lines can be observed by the *Copernicus* satellite. These curves, from Shapiro and Moore (1976), are for a plasma whose temperature is not changing with time; the curves exhibit a significant shoulder on the left side if the gas is allowed to cool radiatively since the recombination rate is slower than the cooling rate. For comparison, the X-ray emissivity of the plasma in the lowest energy bands of the Wisconsin experiment is shown by the dashed curves (see Cox 1977).

neutral or weakly ionized atoms, and the minimum velocity dispersion for O VI components is consistent with the doppler broadening expected for a low-density plasma whose temperature gives a maximum fraction of the five-times ionized species of oxygen.

The first survey of O VI absorption over many different directions was carried out by Jenkins and Meloy (1974), who reviewed the spectra recorded in a general survey of interstellar lines during the satellite's first year in orbit. A more detailed examination of the spectra of a few stars was performed by York (1974), who looked for absorptions by N V and S IV, in addition to measuring those of O VI. The near absence of N V and S IV indicated most of the gas is at a temperature above about 3×10^5 K (York, 1976) -- see Fig. 1. Encouraged by the success of these early observations, Jenkins (1977a) carried out an observing program dedicated to obtaining higher-quality data on O VI toward a well-chosen sample of stars observable by the satellite. The results of this most recent effort, together with conclusions from the earlier work, will be summarized here.

2. CIRCUMSTELLAR INTERPRETATION

An important phase in the analysis of any lines seen in a stellar

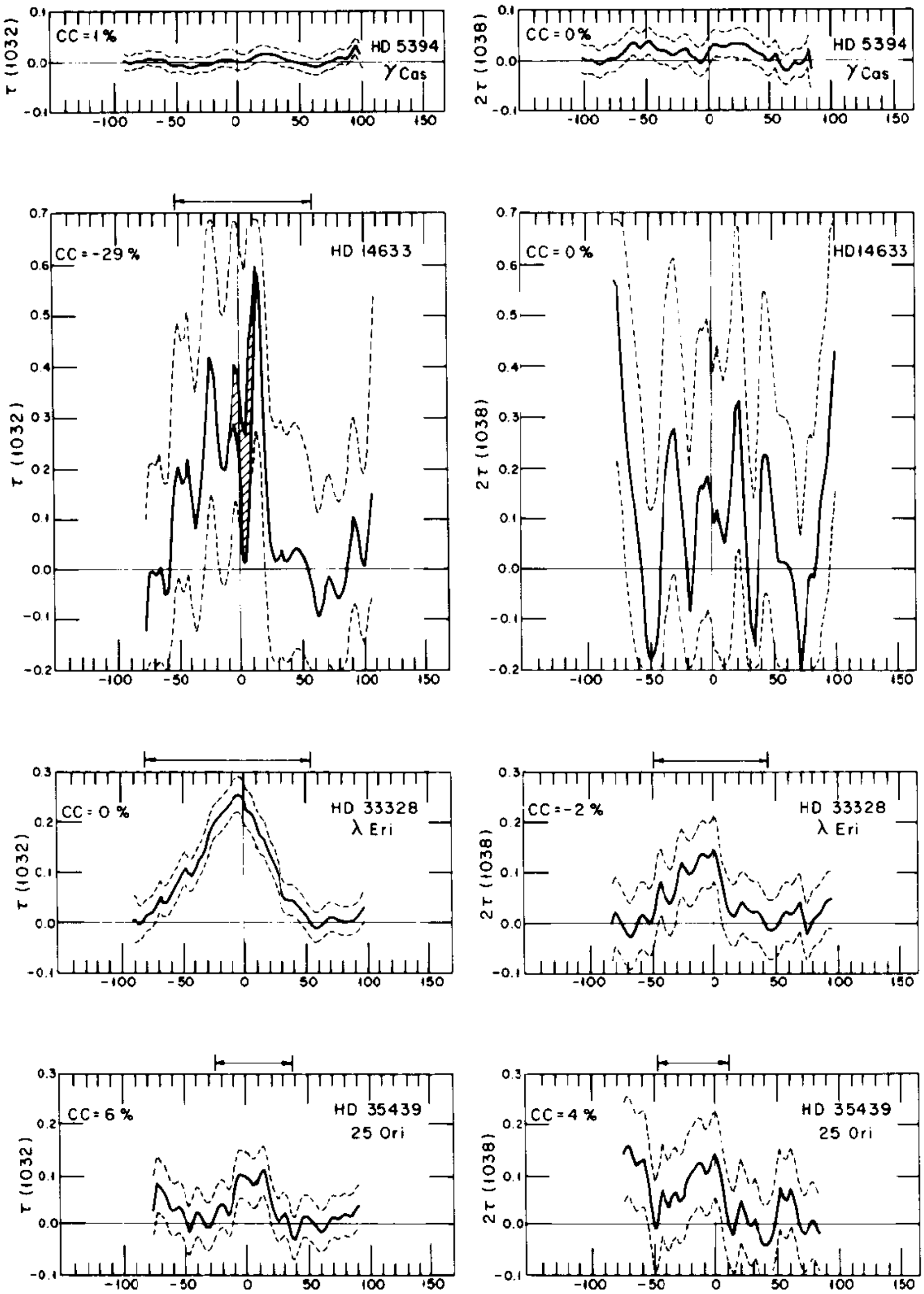

Fig. 2. Typical optical depth tracings for the 1032 and 1038 Å O VI absorptions toward several stars. Velocity scales (abscissae) are in km s^{-1}. Dashed lines on either side of the main traces indicate the envelope of a ± 2σ error due to photon count statistics. In many cases, systematic errors in defining the stellar continuum level are more important. The plots here show the variability in data quality from one star to the next, ranging from poor (HD14633) to excellent (HD36695). An upper limit of 10^{12} cm^{-2} for the column density toward one star, γ Cas, indicates the sun is not immersed in a coronal gas region with a temperature near the O VI peak shown in Fig. 1.

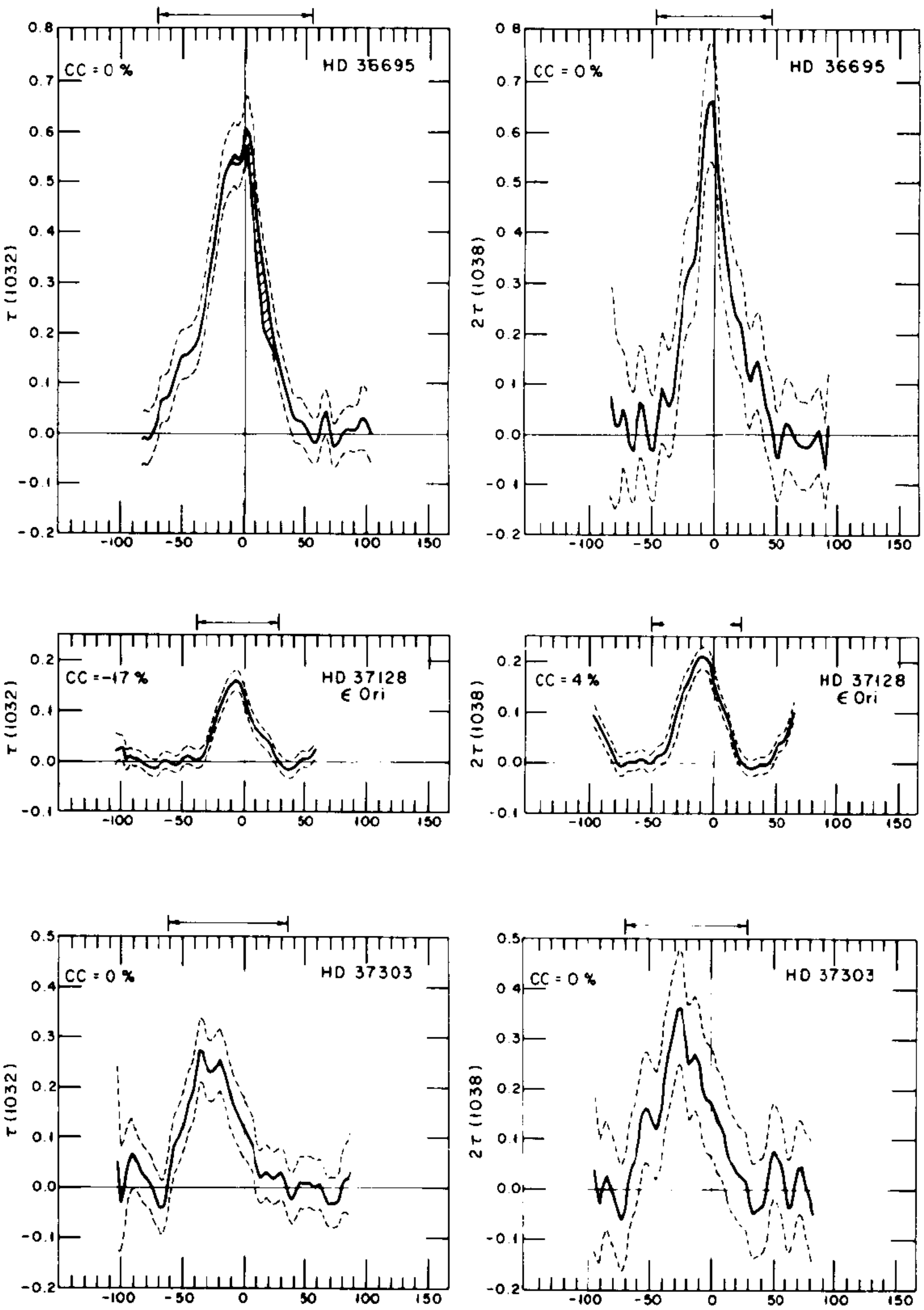

Fig. 2 (continued)

spectrum is to differentiate those originating within the star's photosphere, or a circumstellar shell, from absorptions which are truly interstellar. For stars which are rotating rapidly, O VI profiles are narrower than normal photospheric lines, although Rogerson and Lamers (1975) have identified extremely broad stellar O VI components associated with weak mass-loss activity in the BO V star τ Sco, and strong P Cygni profiles are seen in more luminous stars (Morton 1976). One approach for identifying a circumstellar origin for absorptions of the type shown in Fig. 2 is to rely on a statistical comparison of the data with various attributes of the stars observed.

Fig. 3 indicates that there is no obvious dynamical relationship between the O VI gas and the stars, since the points are scattered

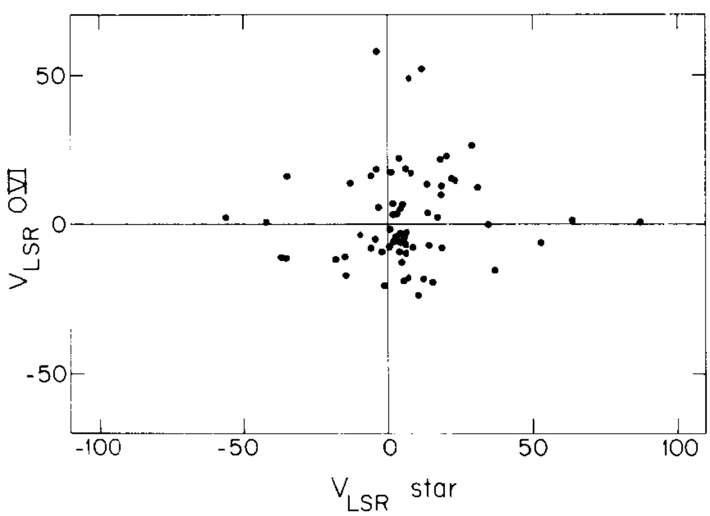

Fig. 3. Velocity centroids of the O VI profiles versus stellar radial velocities. All velocities are corrected to the local standard of rest.

along a horizontal line instead of an incline with a slope of unity. While there seems to be no overall preponderance of negative velocities, such as one might expect if gas were being ejected from the stars, we must acknowledge that an absolute velocity reference for all of the points in the diagram is poorly determined because of a fairly significant uncertainty in the laboratory wavelength of the O VI transitions. Nonetheless, it is still possible the gas may be associated with a star without sharing its velocity; an envelope of hot material may have been produced by the interaction of the star with ambient interstellar gas.

Castor et al. (1975) suggested that as material ejected from early-type stars collides with the surrounding gas, a shock is established and a circumstellar shell of O VI should be observed (see McCray (1977) for a more up-to-date theoretical treatment). Even though their theory suggests the O VI column density varies weakly with the energy deposition rate of the stellar wind, it is still instructive to examine whether or not the amount of O VI seen correlates with mass loss activity which exhibits striking variations over different spectral types.

The bolometric magnitude M_b of a star is a good index for the strength of its P Cygni profiles which show the mass loss (Snow and Morton 1976). An interpretation of the relationship between M_b and the O VI column density N(O VI) is, however, made more complicated by a good correlation between M_b and the star's distance r -- a result of selecting target stars in the survey to a certain limiting apparent brightness in the ultraviolet. We can disentangle the effects of distance and magnitude by examining the three-way regression of log N(O VI), M_b and log r. The analysis shows that at a fixed M_b values of log N(O VI) are well correlated with log r (partial correlation coefficient $\rho = 0.51$), while there is practically no correlation of log N(O VI) with M_b for a fixed log r ($\rho = 0.07$). This lack of correlation, along with other null correlations examined by Jenkins (1977b),

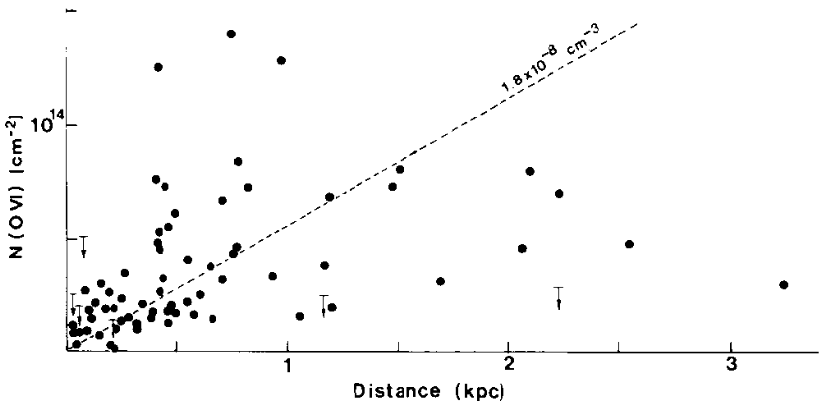

Fig. 4. O VI column density versus distance to the star. The slope of the dashed line corresponds to $\langle n\ (\mathrm{O\ VI})\rangle \equiv \Sigma N\ (\mathrm{O\ VI})/\Sigma r$ for all 72 stars surveyed by Jenkins and Meloy (1974) and Jenkins (1977a). To derive an overall average for the electron density $\langle n_e \rangle$, one should multiply $\langle n\ (\mathrm{O\ VI})\rangle$ by a factor which ranges from 1×10^4 to 5×10^4, depending upon the temperature distribution of the material

offers no encouragement for the O VI being primarily attributable to the effects of mass loss from the star under observation.

3. INTERSTELLAR INTERPRETATION

There is good reason to believe the O VI gas regions may be distributed through much of the interstellar space in our galaxy. The production and maintenance of these regions can be the consequence of the late stages of evolution of supernova remnants, and a general network of coronal gas may be established with a plausible value for the supernova birth rate (Cox and Smith 1974, Smith 1977, McKee 1977).

The observed relationship of N(O VI) with distance is very irregular, even though a meaningful correlation does exist. Large fluctuations about mean densities for various other interstellar species are not uncommon however. In effect, we may interpret the variability in N(O VI)/r as resulting from the random placement of discrete coronal gas domains, and we are viewing statistical fluctuations in the numbers of these regions over various paths. The analysis of these fluctuations by Jenkins (1977b) indicates that roughly 6 regions per kpc, each having a column density of about 10^{13} cm^{-2}, are responsible for about 75% of the gas, while a separate population of thicker, but more sparsely distributed regions makes up the remaining 25%.

An independent confirmation of the discrete domains is provided by the statistics of profiles' velocity centroids and widths. The data are consistent with viewing the superposition of components, each with a mean N(O VI) of 10^{13} cm^{-2} which takes on some particular random velocity. The dispersion of radial velocities corresponds to 26 km s^{-1} after a compensation for the thermal doppler broadening inside each re-