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OBSERVATIONAL ASTROPHYSICS FROM ROCKETS; STELLAR SPECTRA

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The earth's atmosphere is completely opaque to optical radiation that has a wavelength shorter than 3000 Angstroms. For many problems in astrophysics, observations at shorter wavelengths are necessary in order to make theoretical progress. This is brought out by the fact the maximum in the Plank curve for a black body at 10000°K occurs below the atmospheric cut-off. Since most of the naked eye stars have an effective temperature greater than this, it has been impossible to adequately check from the ground the theoretically predicted structure of their atmospheres. The resonance lines of most of the more abundant elements occur at these short wavelengths. Similarly, the electronic transitions of most molecules of astrophysical interest also are in the ultraviolet which is unobservable from the ground. Because of the importance of these problems to physics and astrophysics, our first efforts in the use of space vehicles for astronomical purposes has been in the ultraviolet. The effort being made in this direction ranges from simple photometers in unguided sounding rockets to the implementing of a 36 inch spectrophotometric telescope in an orbiting spacecraft. The following describes our first attempt to obtain ultraviolet stellar spectra and discusses the results.

On November 22, 1961 at 0842 U.T. we launched an Aerobee rocket from the Wallops Island, Virginia launch site containing four objective grating stellar spectrophotometers. The detailed description of the experiment is to be published in the Astrophysical Journal, Vol. 136, No. 1. For the sake of completeness, a brief description will be given here.

The design of the experiment was an extension of the method used by Kupperian, Boggess and Milligan[1] in an Aerobee rocket to obtain nebular isophotes in the ultraviolet, i.e. the instrumentation looks out the side of the rocket and scans the sky as the rocket spins and precesses during free fall. The determination of the rocket's aspect then enables the identification of the objects viewed. The extension of the technique was to let the spin of the rocket accomplish the spectral scan as well as the scan for objects of interest. This is simply done by using an objective dispersive system. Motion of the instrument will cause the displacement of the spectral image. If this displacement is across a slit, spectral scanning occurs. In this experiment two gratings were used in a mosaic as the dispersive element.

The spin rate of the rocket was preselected to give a scan rate of 5000 Angstroms per second. The frequency response of the associated electronics was chosen to match this scan rate. The spectral resolution was 50 A on one pair of spectrophotometers and 100 A on the other. The short wavelength cut-off was λ 1300 for one and λ 1700 for the other in each pair. The wavelengths in the stellar spectra were determined from the zero order image and the spin rate. Ideal dynamic behavior was attained by the rocket.

In Figure 1 is shown a portion of a compressed FM-FM telemetry record. The record is the scanning through two rotations of the rocket. It shows the northern horizon, stars, the southern airglow horizon, and the earth including some cities. Of particular interest to the geophysicist is the asymmetry between the northern and southern horizons. The higher intensity in the north extended to an angular distance of 60° above the rocket horizon. The two shorter wavelength spectrophotometers were saturated throughout the flight although they had lower sensitivity than the longer wavelength ones. We interpret this high surface brightness as being an ultraviolet aurora associated with the November 1960 solar event. This phenomena was completely unexpected on the basis of previous experience.

The sensitivity of each instrument with respect to the others was known and therefore a minimum surface brightness can be given. For the short wavelength spectrometers looking straight up at the peak of the flight (180 km) the minimum surface brightness was more than a factor of ten brighter than that of night Lyman-α.

The minimum value of the sky brightness observed by the long wavelength instruments was 10^{-3} ergs cm^{-2} S^{-1} $strad^{-1}$ if it is assumed that the radiation occurs at 2500 Angstroms where the instruments have maximum sensitivity. While an objective dispersive instrument does not give spectra for extended objects, from the known behavior of the instruments the wavelength interval may be guessed. It appears that the UV radiation was confined to the region below λ 1800. If this is the case, the actual specific intensity was closer to 10^{-2} ergs $cm^{-2}S^{-1}strad^{-1}$ for the long wavelength instruments and more than 10^{-1} ergs cm^{-2} S^{-1} $strad^{-1}$ looking straight up at 180 km.

It appears as if the rocket flew into and never got out of an atmospheric emission which has not been previously reported. The Lyman-Berge-Hopfield bands of N_2 and the Schumann-Runge bands of O_2 both appear in the 1300-1800 Angstrom region of the spectrum along with the electronic transitions of several other molecules. Observations of the ultraviolet airglow and aurora with instruments designed specifically for this purpose will be necessary to decide the issue.

It should be pointed out that the geometrically quiescent behavior of this ultraviolet aurora along with simultaneous occurrence of a magnetic bay and a disturbed ionosphere presents an interesting problem in respect to the energy source.

Good stellar spectra were obtained for seven stars at 50 A resolution between 1600 and 4000 angstroms. For eight other stars usable spectra were obtained over part of the range of interest. The relative energy distribution was good to ten or twenty percent and the absolute energy to thirty percent.

The spectrum of each star was compared with a theoretical model atmosphere computed to represent the same spectral class. One star, α Carinae, FoIa, the lowest temperature star observed, was in very good agreement with the appropriate model atmosphere. For the rest from AoV to 0_5f and Wc7 a deficiency in flux started at λ 2400. This discrepancy increased to more than a factor of ten at λ 1800. A sample spectrum is shown in Figure 2.

Arguments may be given to show that this is an intrinsic property of the stellar atmosphere (Stecher and Milligan, Astrophysical Journal, 136 #1 in press) and not due to absorption between the instrument and the star. This presents the problem of the source of opacity in stars.

A theoretical model stellar atmosphere is calculated from a temperature distribution through the atmosphere obtained by solving the radiative transfer problem under conditions of local thermodynamic equilibrium and then numerically solving the equation of hydrostatic equilibrium. It is tested by requiring the flux to remain constant at each point in the atmosphere.

Since the structure of the atmosphere is dependent upon the opacity as a function of depth, a detailed knowledge of the chemical composition and the absorption coefficient for each atom and ion is necessary. It is at this point where the compromise is usually made. For the early type stars it is generally assumed that absorption is due to hydrogen and helium since these are by far the most abundant constituents. Electron scattering is also taken into account. The atomic absorption by heavier elements is generally considered unimportant. A number of B star models have been computed for a pure hydrogen atmosphere since helium only contributes ten percent of the opacity in this temperature range. The frequency dependence of the hydrogen continuous absorption coefficient is such that the gas becomes quite transparent on the low frequency side of a series limit. This results in a large increase in flux over that of a black body on the low frequency side of the Lyman limit. It is in this region that we now have observations which disagree with the models.

The problem of the observed absorption is complicated by the wide range of temperature over which it is present. The form of the absorption is suggestive of molecules. While certain molecules are important in cool stars in the hot stars these same molecules would be dissociated and the constituent atoms ionized. It would appear that only hydrogen and helium are abundant enough for consideration at a constituent of a molecule. A number of molecules and quasi-molecules may be formed out of various combinations of hydrogen and helium atoms and ions. The quasi-molecule of H_2 will absorb in this region while H_2 itself will not.[2] H_3^+ should be considered for those stars where H_2^+ and H^- are important since it has a much larger binding energy.[3] HeH^+ has a stable ground state.[4] It could be important in either its quasi or molecular form but at this time its optical transitions are unknown.

The exact wave functions for HeH^{++} have been computed for a number of states.[5] Oscillator strengths have also been computed and are high.[6] The 2pσ state is a partially attractive one with a rate coefficient for formation that is very high and almost independent of temperature.[7] Absorptions from it fall in the proper region of the spectrum to be of interest.

The basic difficulty with a molecular source of opacity in a stellar atmosphere is that the number of molecules per unit volume is proportional to the product of the number density of the component constituents. The emergent flux for an atmosphere in local thermodynamical equilibrium is given by

$$1. \quad F_\nu(\tau=0) = 2\int_0^\infty S_\nu(\tau_\nu)\, E_2\, (\tau_\nu)\, d\tau_\nu \quad ,$$

where $S_\nu(\tau)$ is the source function. The optical depth at frequency ν, τ_ν is obtained from the mass absorption coefficient, κ_ν, by

$$2. \quad d\tau_\nu = -\kappa_\nu \rho dx.$$

E_2 is the exponential-integral function. From this it is immediately obvious that the frequency dependance of the absorption coefficient will cause the emergent flux for different frequencies to originate from physically separate layers.

The boundary conditions require that the temperature increase with physical depth. This requires a high optical depth near the physical boundary of the star in order to obtain agreement with the observations which require $S_\nu(\tau_\nu)$ to be small and the density to be low. Thus high absorption at low density and temperature is necessary.

Model stellar atmospheres are further complicated at this point by several other difficulties. It has been shown that the luminosity for a star in radiative equilibrium is completely determined by the mass.[8] Under the assumption that the masses for B stars are well known; we are unable from the observations, to account for half of the stars luminosity. One possible solution to this would be in the re-radiation of a molecular absorber. HeH^{++} for instance can absorb radiation in the 2pσ state by the 2pσ - 3dσ transition and re-radiate by 3dσ - 1sσ transition giving a continuum below λ 304. Such a mechanism would have interesting consequences on the ionization of the interstellar medium. Another mechanism to account for the needed flux is through particle radiation[9] which can also explain[10] the nebular radiation observed at λ 1300.[1]

The observed high opacity will steepen the temperature gradient probably to the point where it will exceed that of the adiabatic gradient and convective energy transport will result. Convection must be present to provide energy for the magnetic field necessary for corpuscular radiation if it is to be invoked as the energy loss mechanism. Convection would also be expected to produce a large high temperature corona. It may be mentioned that the hydrodynamic problem for this type of convecitve equilibrium has yet to be solved by the theoretician. Computation of model stellar atmospheres appears to be a very difficult problem.

An important consequence of the observation is the necessary revision of the interstellar radiation field. Dunham[11] made the classical calculation of the interstellar radiation field by assuming that each star radiated as a black body. Lambrecht and Zimmerman[12] have recalculated the field using model atmospheres and comprehensive counts of the number of stars in each spectral class at each magnitude. The large discrepancy in flux observed in the ultraviolet makes a considerable difference in these and other calculated radiation fields.

Stromgren[13] has written the classic paper on the ionic concentration of the elements in the interstellar medium.

The state of ionization of those atoms and ions whose ionization potential is more than 5 e.v. is determined by the flux in the radiation field which must be changed. The recalculation of abundance ratios, temperature, and densities, now in progress, may considerably change the detailed picture of the interstellar medium.

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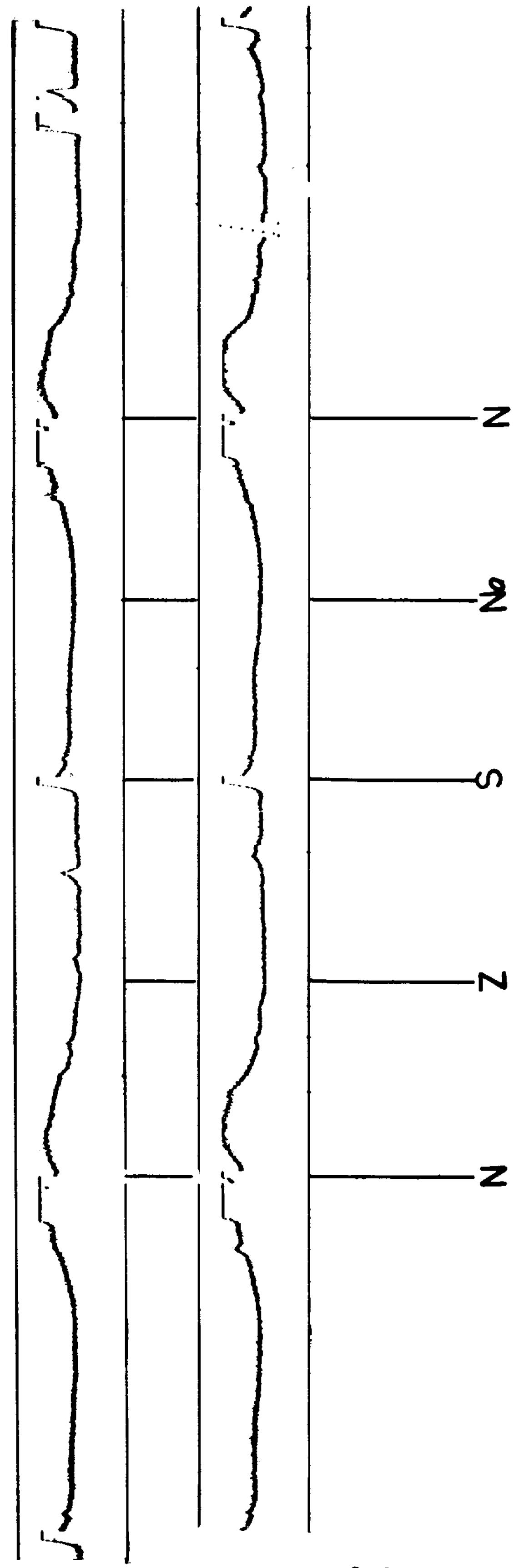
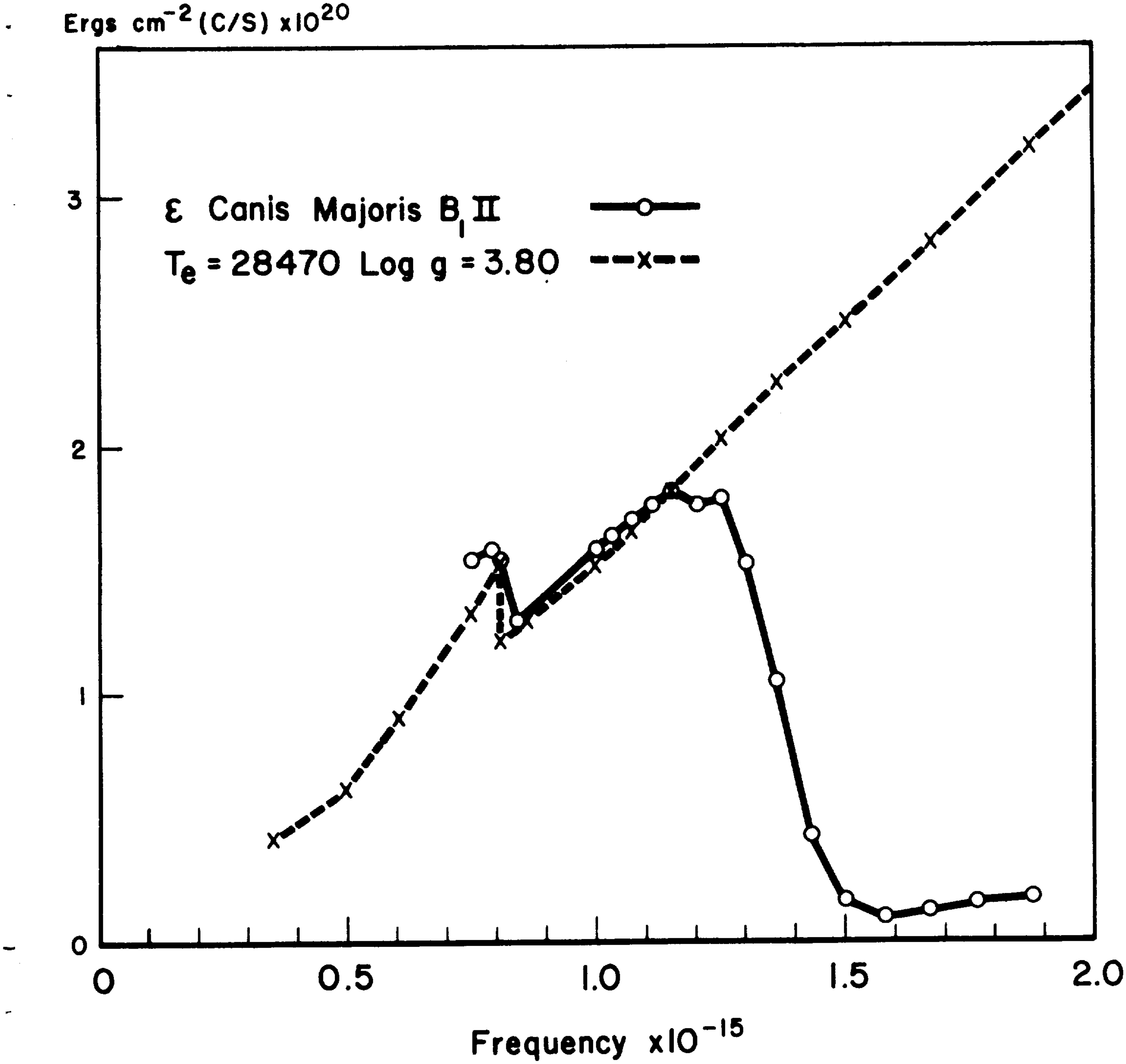
Figure 1. Compressed FM-FM telemetry record showing the scan of a spectrophotometer as the rocket spins. The difference between the northern and southern horizon is to be noted. Star signals also appear.

Figure 2. The solid lens is the observed absolute flux of ε Canis Majoris, B, II. The dashed line is a model atmosphere for T_e = 28470 and log g = 3.80. The theoretical flux curve[14] has been arbitrarily normalized to observe one at $\nu = 10^{15}$ c.p.s.





Ergs cm^{-2} (C/S) x10^{20}
ε Canis Majoris B_1 II
T_e = 28470 Log g = 3.80
3
2
1
0
0
0.5
1.0
1.5
2.0
Frequency x10^{-15}