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LIMITS ON THE SPACE DENSITY OF O SUBDWARFS AND HOT WHITE DWARFS FROM A SEARCH FOR EXTREME ULTRAVIOLET SOURCES

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ABSTRACT

An area of approximately 1350 square degrees toward the galactic anticenter has been searched for sources radiating at extreme ultraviolet wavelengths. Discrete sources within this region were not detected at fluxes above the level set by the instrument sensitivity, 2.9×10^{-8} ergs cm^{-2} s^{-1} in the 135–475 Å band. These results, combined with those of a previous search of the north galactic pole, are used to place limits on the space density of 0 subdwarfs and hot white dwarfs.

Subject headings: stars: early-type — stars: stellar statistics — stars: subdwarfs — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

The region of the Hertzsprung-Russell diagram from 50,000 K to 200,000 K is almost completely unexplored. This is because objects of these temperatures are too hot for accurate studies in the visible band and too cool for studies at X-ray wavelengths.

Recently Greenstein and Sargent (1974) have reported their observations of objects, classified as sdO stars, with effective temperatures greater than 30,000 K and luminosities between 10 and $100L_{\odot}$. Carnochan *et al.* (1974) have observed with the TD1 satellite many objects emitting between 1350 and 2890 Å that have large ultraviolet excesses and which may be related to the sdO objects. Carnochan *et al.* estimate the space density of the objects they observe to be greater than 8×10^{-5} pc^{-3}, but until more extensive studies of these objects are made it is difficult to determine to what class this spatial density applies.

It is possible to estimate by optical methods that the temperature of the central stars of planetary nebulae ranges from about 60,000 to 200,000 K, and studies of the spatial density of these objects have been made (cf. O'Dell 1968 for a review). However, the total density of objects identical to the central stars of planetary nebulae is not known, particularly in the low-temperature region, because the surrounding nebulosity becomes difficult to detect as the nebula evolves. The objects which have been observed lie on the extension to higher temperatures of the white-dwarf cooling tracks and are called hot white dwarfs.

Theoretical estimates of the spatial density of hot white dwarfs are dependent on the unknown magnitude of neutrino cooling (Hills 1972). If neutrino emission is not important in the evolution of these stars, then their spatial density is about 1.5×10^{-5} pc^{-3} at an effective temperature of 100,000 K (Rose and Wentzel 1973). If neutrino emission is important, the density is about a factor of 100 less because these objects then evolve faster.

We have obtained new information about the spatial density of sdO stars and hot white dwarfs through a search of a large region of the sky for sources radiating at extreme ultraviolet (EUV) wavelengths. These sources should be emitting most of their radiation in the EUV. We have previously presented the results of the first half of this search about the north galactic pole (Henry *et al.* 1975*b*, hereafter Paper I). This paper describes an EUV search of the galactic anticenter region which extends the area searched for EUV sources to about 7 percent of the sky.

II. OBSERVATIONS

The data were obtained by an EUV focusing collector that was launched by a Black Brant VC Rocket from White Sands Missile Range at 0408 UT 1973 February 10. The instrument is identical to that used to conduct the first search (Paper I). A complete description of the instrument and the calibration procedures used is given by Henry *et al.* (1975*c*), so we will only give a brief description here.

The instrument employed a set of nested gold-coated plane mirrors and a mechanical collimator which together limited the field of view to 1° by 50° (FWHM). The angular response along the long axis of the field was approximately rectangular and along the short axis approximately triangular. Five channel electron multipliers were employed as the photon sensors. These were placed at the focal plane in such a way that the long axis of the field of view was divided into five overlapping, approximately rectangular segments. In front of each detector was a filter composed of approximately 1500 Å of aluminum upon which was deposited about 150 Å of carbon. The filter thicknesses were determined by transmission measurements at 304 and 584 Å. The detectors were calibrated at 304 Å against a gold photodiode standard. The quantum efficiency of each detector was extrapolated to other wavelengths by normalizing the measurements of Weller and Young (1970), Manson (1973), and

Parkes, Gott, and Pounds (1970) to our measurements at 304 Å.

The peak value of the effective area per detector including all efficiencies was about 0.25 cm^2 at 175 Å. This value varied by ± 30 percent over the five detectors. The bandpass of the instrument, as defined by the wavelengths at which the effective area fell to 10 percent of its peak value, was approximately 135–475 Å.

During the flight one of the detectors malfunctioned and gave no signal. The altitude dependence of the counting rates of the other four detectors was consistent with atmospheric absorption of the expected principal source of background, the geocoronal airglow emission at 304 Å. Hence, we conclude that the four detectors which returned data were responding primarily to EUV radiation and not to charged particles or far-ultraviolet radiation.

The aspect of the detectors was obtained from star-field photographs taken by an onboard 35 mm camera, star transits in an ultraviolet telescope of the type described by Holberg, Bowyer, and Lampton (1973), and integration of vehicle slewing rates as measured by the attitude control system. A total of approximately 1350 square degrees, as determined by the half-power beam widths, was surveyed as is shown in galactic coordinates inFigure 1.

No discrete EUV sources were detected by the instrument. The upper limit that may be placed on the flux from any such source is dependent on its position in the survey region because of the changing scan rates and atmospheric corrections throughout the flight. The weakest upper limit at the 95 percent ($2\,\sigma$) confidence level is 5.8×10^{-8} ergs cm^{-2} in the 135–475 Å band, but this applies to less than 1.5 percent of the survey region. The $2\,\sigma$ limit averaged over the entire survey region, exclusive of the shaded areas in Figure 1, is 2.9×10^{-8} ergs cm^{-2} s^{-2} in the 135–475 Å band. The shaded areas are positions at which long integration times occurred, so that the limits for these regions are substantially more stringent than the average. The $3\,\sigma$ limits for these regions are 6.0×10^{-9} ergs cm^{-2} s^{-1} in the 135–475 Å band.

The atmospheric correction was calculated using the CIRA (1965) model atmosphere appropriate at the time of the flight. This correction, which was never greater than a factor of 2, was computed at 300 Å, the center of the bandpass, and was assumed to apply over the entire band. The conversion factor from counts per second to flux is to some extent dependent upon the assumed source spectrum. To determine the degree of this dependence a number of power-law source spectra were folded through the instrument with spectral indices varying from -2 to $+2$ at the source. The effect of interstellar absorption was calculated by assuming hydrogen column densities between 10^{18} and 10^{19} atoms cm^{-2} in combination with the EUV cross sections of Cruddace *et al.* (1974). Based on the spread of individual conversion factors from their mean, there is no more than a ± 15 percent uncertainty in the conversion from counts per second to flux.

III. DISCUSSION

Of the various discrete sources of EUV radiation which have been proposed, only the nearest hot white dwarfs and O subdwarfs (Hills 1972; Greenstein and Sargent 1974) and U Geminorum stars during a

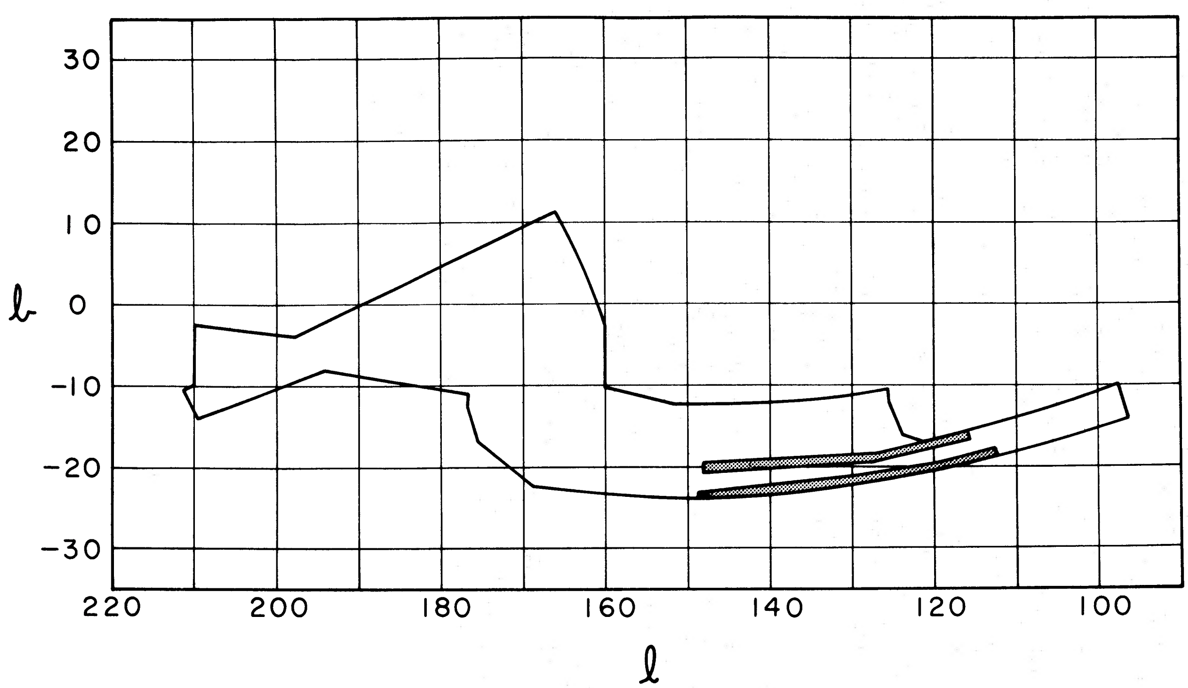

FIG. 1.—The area surveyed in galactic coordinates

flare (Bath *et al.* 1974) are expected to be sufficiently intense that they could have been detected during this survey and the survey described in Paper I. The only U Geminorum star in the survey region that was observed to be flaring at optical wavelengths at the times of these flights was RX And. The observations of this object have been discussed previously (Henry *et al.* 1975*a*).

We may use the results presented here and in Paper I to place a limit on the space density of O subdwarfs and hot white dwarfs. The limit on the density of a class of object is given by

$$n < (\tfrac{4}{3}\pi D_{\max}{}^3 f)^{-1}\,, \qquad (1)$$

where f is the fraction of the sky surveyed, and $D_{\max}$, which depends on the luminosity of the objects and the interstellar absorption, is the maximum distance at which the object can be detected. We determine $D_{\max}$ by solving the equation

$$N = \int_{\lambda_1}^{\lambda_2} d\lambda \frac{L(\lambda)}{4\pi D_{\max}{}^2} \exp\left[-n_{\rm H}\sigma_e(\lambda) D_{\max}\right] A_E(\lambda)\,, \qquad (2)$$

where N is the 2 σ limit on the counting rate from any source in the survey region, $L(\lambda)$ is the luminosity of the source per unit wavelength, $n_{\rm H}$ is the interstellar hydrogen density, $\sigma_e(\lambda)$ is the effective cross section of the interstellar medium per hydrogen atoms, and $A_E(\lambda)$ is the effective area of the detector.

We assume that $L(\lambda)$ is a blackbody spectrum. The luminosity-temperature diagram for hot white dwarfs (O'Dell 1968) is consistent with these objects having a constant radius independent of temperature. Although there is considerable scatter, due partially to a range in masses, the luminosity-temperature diagram can be fitted to an accuracy suitable for our purposes by a radius of 1.3×10^9 cm. The luminosity-temperature diagram for the O subdwarfs (Greenstein and Sargent 1974) is a band centered on a constant luminosity of 50 $L_\odot$ and extending from about 20,000 to 55,000 K. We have extrapolated the measurements of Greenstein and Sargent to 100,000 K, where the sdO stars intersect the cooling curve of the hot white dwarfs, so that we approximate all sdO stars by a luminosity of 50 $L_\odot$ and a temperature range of 20,000 to 100,000 K.

To proceed further we need an estimate of the density of the neutral hydrogen within about 100 pc of the Sun. In Table 1 we list determinations of the interstellar neutral hydrogen density derived from

TABLE 1

Interstellar Neutral Hydrogen Densities as Derived from Stars Closer than 100 Parsecs

Star	Distance (pc)	$n_{\rm H}$ (cm^{-3})	Reference
α CMi....	3.5	0.015–0.030	Evans *et al.* 1975
β Gem....	10.7	< 0.15	McClintock *et al.* 1975
α Boo....	11.1	< 0.1	Moos *et al.* 1974
α Aur.....	14	0.01–0.025	Dupree 1975
α Tau.....	20.8	< 0.2	McClintock *et al.* 1975
α Leo.....	22	0.02	Rogerson *et al.* 1973
σ Eri.....	28	0.07	Rogerson *et al.* 1973
α Pav.....	63	< 0.1	Bohlin 1975
α Sgr.....	80	< 0.12	Bohlin 1975
α Vir.....	99	< 0.03	Bohlin 1975
β Cen.....	99	0.11	Bohlin 1975

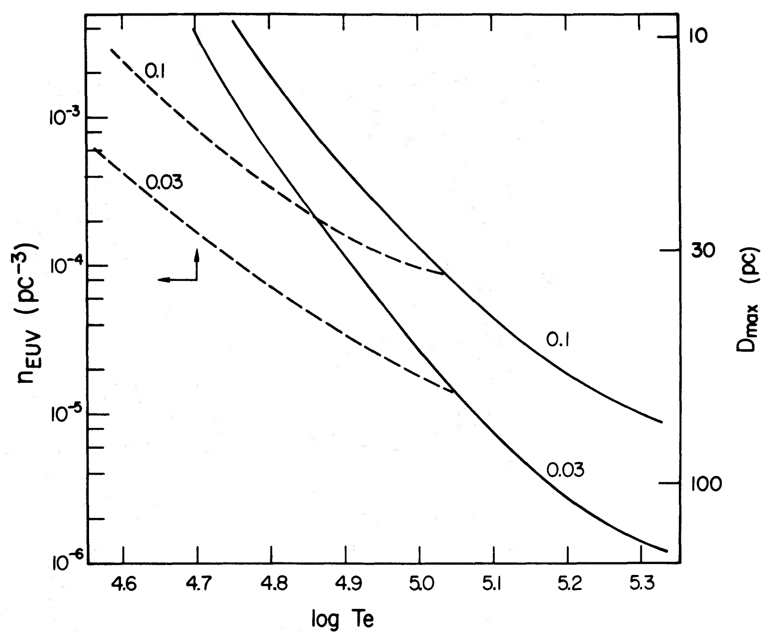

Fig. 2.—Upper limits on the space density of O subdwarfs (*dotted lines*) and hot white dwarfs (*solid lines*) as a function of effective temperature for two values of assumed interstellar neutral hydrogen density. The maximum distance at which the object could be detected with this instrumentation, $D_{\max}$, is also indicated. The solid arrows are the lower limits on the objects described by Carnochan *et al.*

hydrogen Lα absorption measurements at 1216 Å against stars that are closer than 100 pc. These data indicate that the Sun is in a low-density region with n_H less than 0.1 cm^{-3}.

We show in Figure 2 the upper limits on the space density of O subdwarfs and hot white dwarfs determined by the extreme ultraviolet data presented here and in Paper I for two values of the interstellar neutral hydrogen density. The space density of the hot white dwarfs at a temperature of 100,000 K is less than 1.2×10^{-4} pc^{-3}. Although this is the only experimental determination of this quantity to date, it is still a factor of about 10 higher than what is estimated on theoretical grounds. We also show in Figure 2 the limit on the space density of the objects observed by Carnochan *et al.* (1974). This limit applies to objects less than 50,000 K (Wolff, Pilachowski, and Wolstencraft 1974). If these objects are O subdwarfs, then our data combined with the data of Carnochan *et al.*, constrain the space density of these stars to be between about 10^{-4} and 10^{-3} pc^{-3}.

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