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SIRIUS B: A THERMAL SOFT X-RAY SOURCE?

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ABSTRACT

The soft X-rays observed from the Sirius system can be readily explained as thermal emission originating from deep layers of the atmosphere of the white-dwarf star Sirius B, as long as the atmosphere of Sirius B is helium- and metal-poor.

Subject headings: stars: white dwarfs — X-rays: sources

Recently Mewe *et al.* (1975*a*, *b*) announced the detection by the Astronomical Netherlands Satellite (ANS) of soft X-rays from Sirius. The indicated luminosity in their frequency range, which peaks at 0.26 keV, is $(9.1 \pm 1.6) \times 10^{27}$ ergs s^{-1}. They consider and rule out two possible explanations for this flux: a hot corona around Sirius A and accretion onto Sirius B. Several years ago an effective temperature of 32,000 K and a surface gravity of $\log g = 8.65$ were derived from optical observations of Sirius B (Greenstein, Oke, and Shipman 1971). This high temperature has since been confirmed by photometry in the far-ultraviolet (~1100 Å [Savedoff *et al.* 1975]) and visible (Rakos 1974) regions of the electromagnetic spectrum. As the radius of Sirius B is known to be 0.0078 $R_\odot$ from the earlier analysis, an unequivocal comparison of model-atmosphere predictions and observations can be made.

I calculated X-ray fluxes for several model atmospheres with atmospheric parameters listed in Table 1. Model 1 is the one with the atmospheric parameters derived earlier, while model 2 is still consistent with the earlier analysis. All calculations were made with the ATLAS computer program (Kurucz 1970), using compositions of pure hydrogen in accord with earlier analyses of other white dwarfs (Shipman 1972; see below). The usual opacity sources were included: H, H_2^+, H^-, electron scattering, and Rayleigh scattering. No flux was transported by convection, as the atmosphere is stable against convection at all depth points. The stability of the atmosphere rules out a hot corona around Sirius B as a possible explanation for the soft X-ray flux, as convection is needed in order to heat the corona (Böhm and Cassinelli 1971). Only helium-rich white dwarfs, such as those described by Böhm and Cassinelli, are unstable against convection at the high temperatures considered here. The run of temperature with pressure and depth for model 1 is presented in Figure 1, where *m* refers to the mass in grams above a given point in the atmosphere.

When an outside observer looks at a stellar atmosphere, his vision penetrates to optical depth unity in the frequency region he observes in. Points of unit monochromatic optical depth are indicated for various frequency regions. Evidently, someone looking at the star in the X-ray part of the spectrum will see a much hotter star than an optical observer.

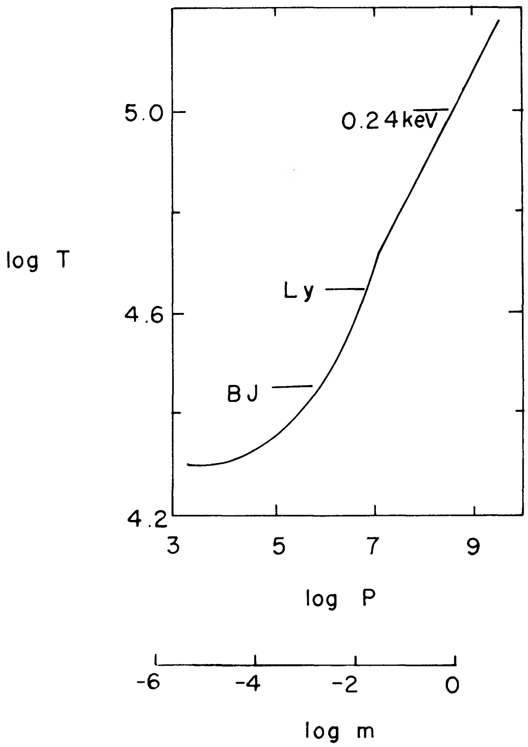

FIG. 1.—The temperature-pressure profile for model 1 of the Sirius B atmosphere. The points of optical depth unity at the Balmer jump (BJ), the long-wavelength edge of the Lyman limit (Ly), and the soft X-ray region (0.24 keV) are indicated. Temperatures are in kelvins and pressures are in cgs units.

The emergent fluxes from model 1 are shown in Figure 2. Here, as elsewhere in this paper, they are given in ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} so that $\int H_\nu d\nu = \sigma T_{\rm eff}^4/4\pi$. The flux measured by Mewe *et al.* (1975*a*, *b*) is shown as a box, with the width of the box their approximate bandpass and the depth of the box their quoted error (not including calibration error). It is gratifying that the model is on target, as the temperature and surface gravity of the model were determined previously. One need only presume a low helium abundance in order to fit the data.

Yet the frequency dependence of the model's emergent flux is so steep that it is useful to compare the

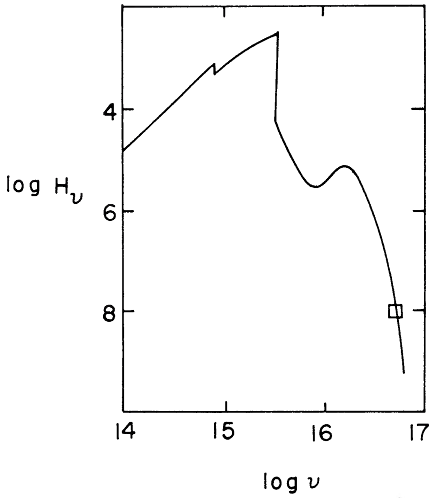

FIG. 2.—The emergent flux from model 1. The increase at log $\nu \sim 16.3$ is due to the increasing transparency of the atmosphere in these wavelength regions. The box indicates the X-ray observations of Mewe *et al.* 1975*a*, *b*.

observed counting rate with a predicted counting rate r, given by

$$r = \frac{4\pi R_*^2 A_{\rm eff}}{D^2} \int \frac{H_\nu}{h\nu} R(\nu) d\nu\,, \tag{1}$$

where R_* is the radius of Sirius B, D its distance from the Earth (2.67 pc, Jenkins 1963), $A_{\rm eff}$ the effective detector area, and $R(\nu)$ the detector efficiency. From observations of the Cygnus Loop, Mewe *et al.* (1975*b*) give a value of 5.555×10^{10} counts ergs^{-1} cm^{-2} for the product $(A_{\rm eff} R(\nu)/h\nu)$ at the frequency of peak detector response, 6.29×10^{16} Hz or 0.26 keV. They note that this absolute flux calibration is uncertain by a factor of 2. Equation (1) then becomes

$$r = 3.05 \times 10^{-9} \int \frac{6.29 \times 10^{16}}{\nu} \frac{R(\nu)}{R(6.29 \times 10^{16})} H_\nu d\nu\,, \tag{2}$$

where the constant has a factor 2 uncertainty.

The integrand of equation (2) contains two terms with steep and opposite frequency dependencies, as the flux falls rapidly with frequency and the detector response rises rapidly. Consequently some care is needed in correctly representing the ν dependence of both $R(\nu)$ and H_ν. I find that the expression

$$H_\nu = C_1 \exp\left(-C_2 \nu_{16}\right)\,, \tag{3}$$

where $\nu_{16} = \nu/10^{16}$, fits the model fluxes with errors of less than a few percent in frequency regions that contribute counts. C_1 and C_2 depend on the model and are listed in Table 1.

A 3.6 μ polypropylene filter cuts off low-energy photons in the ANS detector and thus determines the behavior of $R(\nu)$ for $\nu < 6.29 \times 10^{16}$ Hz. The transmission of such a filter is given by $\exp(-\tau)$ where τ is the filter's optical thickness. As the filter absorbs photons by photoionization, a ν^{-3} dependence of τ on ν is characteristic of all such filters (Sandstrom 1957; Milledge 1965). The transmission curve of the ANS (Brinkman, Heise, and de Jager 1974) can thus be represented by

$$R(\nu) = 8.92 \exp\left(-543.87/\nu_{16}^3\right) \tag{4}$$

for $\nu < 6.29 \times 10^{16}$. Equation (4) has been normalized so $R(6.29 \times 10^{16}) = 1$ and fits the transmission curve as accurately as the graph can be read.

The counting rate r can then be determined by using equations (3) and (4) in equation (2) and numerically integrating equation (2) from 2×10^{16} Hz to 6.29×10^{16} Hz. Computations showed that no significant counts came from photons with $\nu > 6.29 \times 10^{16}$, where equation (4) is no longer an accurate representation of the detector, so this high-frequency region was ignored. The lower limit to the numerical integration of 2×10^{16} Hz was selected arbitrarily; as 80 percent of the counts come from the frequency region $4.5 \times 10^{16} < \nu < 6 \times 10^{16}$, the choice of the lower limit of integration is not material to the results. The computed counting rates from various models are listed in Table 1. These results are uncertain by a factor of 2.4 due to two calibration errors: a factor of 2 uncertainty comes from the uncertain absolute flux calibration, and another 20 percent uncertainty comes from uncertain constants in equation (4).

The observed counting rate, to be compared with the predicted rates of Table 1, is 0.58 ± 0.10 counts s^{-1}. All of the models are compatible with this observation at the 2 σ level, considering the calibration uncertainty of a factor of 2.4, though model 2 provides the best fit. Both models 1 and 2 are compatible with the earlier $T_{\rm eff}$ determination (Greenstein, Oke, and Shipman 1971), *UBV* photometry (Rakos 1974), and far-ultraviolet photometry (Savedoff *et al.* 1975). It is worth noting that there is no way of making a model that is consistent with Rakos's suggestion that Sirius B was a red giant in Ptolemy's time, as the temperature and radius of Sirius B indicate that it has been a white dwarf for at least 3×10^7 years according to the cooling curves of Lamb and Van Horn (1975; cf. Lindenblad 1975). Thus the present analysis confirms the earlier estimate of the effective temperature of Sirius B and suggests that Sirius B is the X-ray source observed by ANS.

A rather critical presumption of the present analysis is that the X-ray opacity in the Sirius B atmosphere is provided by hydrogen alone. Either helium or metals

TABLE 1

MODELS FOR SIRIUS B

MODEL	($T_{\rm eff}$, log g)	FLUX REPRESENTATION C_1	C_2	PREDICTED COUNTING RATE
1...	32,000, 8.65	6.61×10^{-4}	2.0562	0.17
2...	33,500, 8.65	3.51×10^{-4}	1.68651	0.64
3...	35,000, 8.65	4.46×10^{-4}	1.61039	1.21
4...	33,000, 8.80	7.50×10^{-4}	1.99211	0.27

could provide significant X-ray opacity were they present in sufficient quantities. With a minimally acceptable counting rate of 0.16 (2 σ less than the observed rate and stretching the calibration in the right direction) the helium abundance must be less than about 3×10^{-5} by number (model 1) or 2×10^{-4} (model 2). The opacity calculations of Brown and Gould (1970) indicate that $n(\mathrm{O})/n(\mathrm{H})$ must be less than about 10^{-6}, 1.6×10^{-3} of the solar value (Withbroe 1971), if oxygen, the heavy element that absorbs these X-rays, is not to provide significant opacity.

The low abundance of oxygen is not at all unreasonable for a hydrogen-rich DA white dwarf like Sirius B, as oxygen lines have never been seen in a DA spectrum. Calcium, which has been seen in the coolest DA's, provides a guide to the heavy-element abundance of these stars; a recent analysis (Shipman 1976) indicates that in the DA star Ross 627 the Ca abundance is 1.4×10^{-4} of the solar value. The helium-rich DB white dwarfs have rather more dramatic metal depletions; recent analyses give metal abundances between 10^{-6} and 10^{-4} of the solar value, depending on the metal and the star (Wegner 1972). Clearly the present requirement that the oxygen abundance be less than 1.6×10^{-3} of the solar value is consistent with the larger metal depletions observed in white dwarf spectra.

The low helium abundance required by the present model is also consistent with our present knowledge of white dwarfs, but the present limit of 2×10^{-4} (model 2) is a significant extension of the observational upper limit of 8×10^{-3} (Shipman 1972), though consistent with the larger depletion factors observed for metals. The theoretical mechanism for producing such low abundances is gravitational settling (Schatzman 1958; Strittmatter and Wickramasinghe 1971; Shipman 1972), and the present upper limit should provide a significant constraint on such theories. In view of the upper limit to the hydrogen concentration in helium-rich white dwarfs of 10^{-4} (Strittmatter and Wickramasinghe 1971), the helium depletion requirement is not an insurmountable problem for the present analysis.

The identification of the X-rays from Sirius as thermal emission from the white dwarf is supported by the discovery of the hot DA white dwarf HZ 43 as an X-ray source by Margon *et al.* (1976) and as an extreme-ultraviolet source by Lampton *et al.* (1976). Preliminary calculations indicate that these results can also be explained as thermal radiation from a helium-poor white dwarf atmosphere, and a detailed analysis is currently in progress. The XUV spectral region may also provide a test of the present model, as the predicted flux in the 130–430 Å band from model 2 is only a factor of 2 below the observational upper limit of Patterson, Moore, and Garmire (1975). The closeness of the model to the upper limit suggests that Sirius B may be detectable in the XUV.

To summarize: the soft X-ray flux from Sirius B can be logically explained as thermal emission from the deep layers of a helium- and metal-poor white dwarf atmosphere. I derive two models which are consistent with all the observations: hydrogen line profiles, *UBV* photometry, far-ultraviolet photometry, and the observed soft X-ray flux. These results suggest that hot DA white dwarfs could be a significant class of soft X-ray sources.

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