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X-RAY LUMINOSITIES OF B SUPERGIANTS ESTIMATED FROM ULTRAVIOLET RESONANCE LINES

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ABSTRACT

Superionization in the winds of O and B stars has been explained as a result of Auger ionization by X-rays produced in coronal zones in their outer atmospheres. A recent survey of supergiants by the *Einstein Observatory* detected X-ray emission from stars as late as B2 but obtained only upper limits for later B supergiants. These stars show strong lines of high stages of ionization such as C IV and Si IV in the ultraviolet. We use the observed strengths of these lines to estimate X-ray luminosities for a group of 20 B supergiants. The C IV λ1548 line is a useful X-ray diagnostic for spectral classes from B1.5 to B6, and Si IV λ1394 and Si IV λ1403 are found to be useful from B3 to B9. The N V λ1239 line strength is too sensitive to the diffuse radiation field to be useful for estimating X-ray luminosities of B supergiants. We find that L_x/L_{bol} decreases from $10^{-7.2}$ observed for B0 and B1 stars to roughly $10^{-8.5}$ for late B supergiants.

Subject headings: radiation mechanisms — stars: supergiants — X-rays: sources

I. INTRODUCTION

Recent X-ray observations of O and B supergiants using the Imaging Proportional Counter (IPC) of the *Einstein Observatory* have shown X-ray luminosity to be roughly $10^{-7.2}$ times bolometric luminosity for stars of spectral type B1 and earlier (Long and White 1980; Cassinelli *et al.* 1981). Only upper limits on the X-ray emission were obtained for most later B stars. Since the *Einstein Observatory* is no longer operating, X-ray luminosities for these later B supergiants can only be determined by indirect means.

The presence of X-ray emission from O and B supergiants had been predicted at about the observed luminosity by Cassinelli and Olson (1979, hereafter CO) on the basis of the anomalously high ionization stages seen in the ultraviolet spectra of these stars. In their "corona plus cool wind" model, the high-ion stages are produced by the Auger effect in which two or more electrons are ejected from an atom or ion following K-shell absorption of an X-ray. For ions with 10 or fewer electrons, such as those of carbon, nitrogen, and oxygen, two electrons are ejected. Thus, with the Auger explanation, the O VI lines should be observable as long as O^{+3} is a dominant ion stage, i.e., as late as spectral type B0.5. The persistence of O VI to B0.5 was confirmed by Morton (1979). Similarly, N^{+4} is produced from N^{+2} and C^{+3} from C^{+1} in the winds of stars of later spectral type. Cassinelli and Abbott (1981) report that N V is observed in spectral classes B2.5 and earlier, C IV in B6 and earlier, and Si IV is present but weak down to B9.

In this paper we use the Auger ionization model to estimate the X-ray luminosities of supergiants of spectral types from B1.5 to B9. Our assumed model for the source of X-ray emission in these stars is described in § II. In § III we consider the usefulness of line strengths of Auger enhanced ions as diagnostics of X-ray luminosity for B supergiants. The ultraviolet observations of Cassinelli and Abbott (1981) are used in § IV to obtain fractional C^{+3} and Si^{+3} abundances in the winds of 20 stars. In § V, model calculations are used to find the X-ray luminosities needed to produce these observed ion abundances. Our results are summarized in § VI.

II. THE ASSUMED X-RAY SOURCE MODEL

Long and White (1980) and Cassinelli *et al.* (1981) have found that the observed X-ray luminosities are sufficient to account for the superionization in the winds of O and B stars by the Auger effect. Although the total X-ray luminosity is near that predicted from the corona plus cool wind model, the energy distribution is somewhat softer than had been predicted by CO. If the X-rays were produced only in a slab coronal zone at the base of the wind, the soft X-rays would be strongly attenuated by the overlying wind material. However, observed X-ray energy distributions show relatively little attenuation of the 0.2–1.0 keV flux (Long and White 1980; Cassinelli *et al.* 1981; Cassinelli and Swank 1982). Waldron (1982) has found that the slab corona picture leads to an overestimate of the attenuation because it does not properly account for the conditions in and above the recombination region at the top of the corona.

Another possibility, proposed by Lucy and White (1980), is that the X-rays are produced in shocks in the accelerating regions of the radiatively driven flows. In either case, it is reasonable to approximate the X-ray field in the wind as arising from an unattenuated thermal source near the star.

Cassinelli and Swank (1982) obtained relatively high spectral resolution observations ($\Delta E \approx 160$ eV) of δ Ori (O9.5 I), ζ Ori (O9.5 I), and ε Ori (B0 Ia) using the Solid State Spectrometer (SSS) on the *Einstein Observatory* satellite. Using the line and continuum emissivity calculations of Raymond and Smith (1979), they found that the X-ray energy distributions were like that expected from a thermal source at approximately $3 \pm 1 \times 10^6$ K. The best fits to the IPC data of ε Ori and κ Ori (B0.5 Ia) by Cassinelli *et al.* (1981) corresponded to temperatures of about $2 \pm 1 \times 10^6$ K. In our analysis of later B supergiants, we assume that the X-ray flux is that of an unattenuated thermal source at a temperature T_s of 2×10^6 K located near the base of the wind.

III. ULTRAVIOLET RESONANCE LINES AS X-RAY DIAGNOSTICS

a) The Auger Ionization Model

The superionization stages seen in the ultraviolet spectra of O and B stars typically have very low or "trace" fractional abundances, $g_{\rm ion} \equiv n_{\rm ion}/n_{\rm element} < 10^{-2}$ (Olson 1978; Olson and Castor 1981; Garmany *et al.* 1981). Because of this, the ionization equilibrium calculation can be separated into two nearly independent parts, as discussed by CO. The dominant stages of ionization are determined by the ultraviolet radiation field in the wind; and the fractional abundances of the superionization stages are determined by X-ray ionization of the dominant stages.

To illustrate the quantities needed for our ion abundance calculations, as well as the dependence of superionization stage abundance on X-ray luminosity, we consider the ionization equilibrium of carbon for the case in which C^{+1} is the dominant ion stage. In this case, Auger ionization of C^{+1} is the principal means of producing C^{+3}, so the fractional C^{+3} abundance can be written:

$$g(C^{+3}) = \frac{n(C^{+3})}{n(C^{+1})} = \frac{1}{n_e \alpha(C^{+2})} \int_{\nu_K}^{\infty} \frac{4\pi}{h\nu} a_\nu^K(C) J_\nu^x \, d\nu . \quad (1)$$

Here $a_\nu^K(C)$ is the K-shell photoionization cross section for carbon with threshold frequency ν_K (corresponding to 0.3 keV), n_e is the local electron density, and $\alpha(C^{+2})$ is the recombination coefficient of C^{+3} to C^{+2}. The mean intensity in the X-ray region is given by

$$J_\nu^x = W F_\nu^x = W \frac{L_\nu^x}{4\pi^2 R_*^2}, \quad (2)$$

where W is the dilution factor and R_* is the star's radius. The X-ray luminosity can be expressed

$$L_\nu^x = {\rm EM}_s \Lambda_\nu(T_s), \quad (3)$$

where ${\rm EM}_s = \int n_e^2 \, dV$ is the volume emission measure of the X-ray source region and $\Lambda_\nu(T_s)$ is the emissivity (ergs cm^3 s^{-1} Hz^{-1}) from the program of Raymond and Smith (1979).[1] Using the conservation of mass equation, the electron density can be written in terms of the mass loss rate $\dot{M}$ and wind velocity $v(r)$ as

$$n_e = \frac{\rho}{\mu_e m_{\rm H}} = \frac{\dot{M}}{\mu_e m_{\rm H} 4\pi v(r) r^2}, \quad (4)$$

where $\mu_e m_{\rm H}$ is the mean particle mass per electron. Combining equations (1) through (4), and using $v(r) = v_\infty$ and $W = 0.25(R_*/r)^2$ for regions far out in the wind, we obtain

$$g(C^{+3}) = \frac{\mu_e m_{\rm H} v_\infty {\rm EM}_s}{\alpha(C^{+2}) \dot{M}} \int_{\nu_K}^{\infty} \frac{a_\nu^K(C) \Lambda_\nu(T_s)}{h\nu} d\nu . \quad (5)$$

We see from this that to calculate the fractional abundance of a superionization stage, we must specify the temperature and emission measure of the X-ray source region, the mass loss rate, the terminal velocity v_∞, and the electron temperature in the wind (which determines the recombination coefficient). Note also, from equation (3), that the C^{+3} abundance is directly proportional to the X-ray luminosity beyond 0.3 keV.

b) The Dependence of Ion Abundances on the Diffuse Radiation Field

In the above example, we have assumed C^{+1} to be the dominant ionization stage. In fact, the determination of the dominant stages can be somewhat uncertain due to the dependence on the diffuse radiation field, which is strong in winds which are optically thick in the far-ultraviolet continuum. For the O4 If star ζ Pup, CO assumed that the ultraviolet radiation field in the wind was composed of a dilute photospheric field attenuated by the opacity of the underlying wind material and an ambient field proportional to the Planck function at the local electron temperature. Because the diffuse field

[1] For the case in which the X-ray source is truly confined to a region just above the photosphere, the right-hand side of equation (3) should be multiplied by 0.5 since only X-rays emitted in the outward 2π sr contribute to the luminosity. The X-rays may in fact be emitted from a more extended region, so this geometrical factor is somewhat model dependent. We take this factor to be unity, so that our derived X-ray luminosities are consistent with those of Cassinelli *et al.* (1981).

strength is very uncertain and model dependent, we choose to estimate X-ray luminosities using only those superionization lines for which the ion abundance is found to be insensitive to the diffuse field.

To determine which lines are useful X-ray diagnostics in this respect, we have calculated the ionization equilibrium in the winds of several B supergiants for two extreme cases, one in which we ignore the diffuse contribution altogether and one in which we assume it to be proportional to the local Planck function. For our calculations, we have used the computer program described by CO. This program solves the ionization equilibrium equations for the elements H, He, C, N, O, Ne, Mg, Si, P, and S, including the processes of radiative, collisional, and Auger ionization and radiative and dielectronic recombination. We include the effects of Auger transitions in ions with more than 10 electrons, in the manner discussed by Weisheit (1974). For the case of no diffuse field, the radiation field is given by

$$J_\nu(r)=W(r)\left[F_\nu \exp\left(-\theta_\nu\right)+F_\nu^x\right], \qquad (6)$$

where F_ν is the photospheric flux from the model atmospheres of Kurucz (1979), $\theta_\nu(r)$ is the radial optical depth measured outward from the photosphere to radius r, and F_ν^x is the unattenuated X-ray flux from a thermal source region at $T_s=2\times10^6$ K. For the second case, we use the approximation of CO that

$$J_\nu(r)=W(r)\left[F_\nu \exp\left(-\theta_\nu\right)+F_\nu^x\right] + B_\nu(T_e)\left[1-0.5\exp\left(-\theta_\nu\right)-0.5\exp\left(-\tau_\nu\right)\right], \qquad (7)$$

where $B_\nu(T_e)$ is the Planck function and $\tau_\nu(r)$ is the optical depth measured inward from an infinite radius to a radius r. We take the wind temperature T_e to be 0.8 $T_{\rm eff}$, which is in the temperature range appropriate for winds in radiative equilibrium (CO; Klein and Castor 1978).

Table 1 shows abundances of N^{+4}, C^{+3}, and Si^{+3} calculated for these two cases for several stars. These values are for a radial distance $r=2R_*$. Following Olson (1978) and CO, we have assumed the "standard velocity law"

$$v^2(r)=v_0^2+v_1^2(1-R_*/r), \qquad (8)$$

with $v_0=v_1/20$. Also, we have used an X-ray source emission measure for each star which gives $L_x/L_{\rm bol}=10^{-7.5}$. Here $L_{\rm bol}$ is the star's bolometric luminosity and L_x is the total X-ray luminosity in the 0.1–4 keV bandpass of the IPC on the *Einstein Observatory*. Values of $T_{\rm eff}$, $L_{\rm bol}$, $\dot{M}$, R_*, and v_∞ are given in Table 2 for all of the stars in the Cassinelli and Abbott (1981) survey. For most of the stars, $T_{\rm eff}$ has been taken from Barlow and Cohen (1977) and $L_{\rm bol}$ has been obtained from the absolute magnitude given by Lesh (1968). Values of $T_{\rm eff}$ and $L_{\rm bol}$ for θ Ara, η CMa, 67 Oph, and β Ori have been taken from the compilation of Abbott (1978). The adopted mass loss rates and terminal velocities are discussed further in § IV.

The last column of Table 1 gives the ratio of the ion abundance calculated with a diffuse field to that calculated for no diffuse radiation. We see that the N^{+4} abundance is very sensitive to the approximation made for the diffuse contribution to J_ν. This is shown for three of the early B supergiants in which N v lines are

TABLE 1
DEPENDENCE OF ION ABUNDANCES ON DIFFUSE FIELD

Ion	Star	Spectral Type	log g[a] w/o df	log g[a] w df	$g_{\rm wdf}/g_{\rm w/odf}$
N^{+4} ...	HD 106343	B1.5	−4.56	−2.73	68
	χ^2 Ori	B2.0	−4.99	−2.94	112
	HD 92964	B2.5	−4.66	−2.77	78
C^{+3} ...	HD 106343	B1.5	−2.20	−2.09	1.29
	55 Cyg	B3	−1.96	−1.86	1.26
	HD 79186	B5	−1.83	−1.74	1.23
	HD 91619	B7	−1.86	−1.80	1.15
	σ Cyg	B9	−1.76	−1.76	1.00
Si^{+3} ...	HD 106343	B1.5	−1.60	−0.44	14.5
	HD 92964	B2.5	−1.45	−1.26	1.55
	55 Cyg	B3	−1.30	−1.32	0.95
	HD 79186	B5	−1.15	−1.19	0.91
	HD 91619	B7	−1.16	−1.20	0.91
	σ Cyg	B9	−1.04	−1.05	0.98

[a] w/o df: without diffuse field; w df: with diffuse field.

TABLE 2

STELLAR PARAMETERS

Star	Spectral Type	$T_{\rm eff}$ (K)	log $L/L_\odot$	$\dot{M}(M_\odot\ {\rm yr}^{-1})$	$R/R_\odot$	v_∞ (km s^{-1})
HD 106343 ...	B1.5 Ia	19000	5.35	5.9×10^{-7}	43	1280
χ^2 Ori	B2 Ia	18000	5.55	1.4×10^{-6}	61	1100
10 Per	B2 Ia	18000	5.31	5.0×10^{-7}	46	990
θ Ara	B2 Ib	21900	5.21	3.2×10^{-7}	29	1180
9 Cep	B2 Ib	18000	5.03	1.6×10^{-7}	34	930
HD 92964	B2.5 Ia	16500	5.22	3.5×10^{-7}	50	920
HD 116084 ...	B2.5 Ib	16500	4.78	5.6×10^{-8}	30	920
3 Gem	B2.5 Ib	16500	4.82	6.6×10^{-8}	32	940
55 Cyg	B3 Ia	15000	5.14	2.5×10^{-7}	55	830
HD 75149	B4 Ia	14300	5.02	1.5×10^{-7}	53	680
HD 79186	B5 Ia	13500	4.93	1.1×10^{-7}	54	650
η CMa	B5 Ia	13200	5.01	1.5×10^{-7}	62	460
ϕ Vel	B5 Ib	13500	4.57	2.4×10^{-8}	35	580
67 Oph........	B5 Ib	13200	4.52	1.9×10^{-8}	36	540
HD 74371	B6 Ia	12900	4.83	6.8×10^{-8}	52	590
HD 125288 ...	B6 Ib	12900	4.39	1.1×10^{-8}	31	520
HD 91619	B7 Ia	12400	4.85[a]	7.6×10^{-8}	58	480
β Ori	B8 Ia	12000	5.05	1.8×10^{-7}	77	350
HD 46769	B8 Ib	11500	4.16	4.4×10^{-9}	31	180
σ Cyg	B9 Ia	10800	4.49[b]	1.7×10^{-8}	50	320

[a]Humphreys 1978.
[b]Rosendhal 1973.

detected. For these spectral types, the dominant ionization stage is N^{+1} for the case of no diffuse radiation field. The presence of a strong diffuse field shifts the dominant stage to N^{+2}. Since N^{+4} is produced by K-shell ionization of N^{+2}, the N^{+4} abundance is greatly enhanced for the case with a strong diffuse radiation field. Because of this strong dependence on the treatment of the diffuse radiation field, we choose not to use the N V lines in B supergiants for estimating X-ray luminosity.

The C^{+3} and Si^{+3} abundances, on the other hand, are seen in Table 1 to be quite insensitive to the strength of the diffuse field. To understand this, consider again the ionization equilibrium of carbon. In the absence of a diffuse field, C^{+1} is the dominant ion stage for B supergiants and the C^{+3} abundance is given by equation (1). A strong diffuse field produces more C^{+2}, and, for stars earlier than about B6, C^{+2} is the dominant ion stage. In this case, C^{+3} is destroyed by recombination into C^{+2}, and it is produced by outer-shell ionization of C^{+2} and by recombination of C^{+4}. Rates for all other production and destruction processes are negligible. Thus, we have

$$n_e n(C^{+3})\alpha(C^{+2}) = n(C^{+2})\int_{\nu_L}^{\infty}\frac{4\pi}{h\nu}a_\nu^L(C^{+2})J_\nu\,d\nu + n_e n(C^{+4})\alpha(C^{+3}), \quad (9)$$

where J_ν is given by equation (7) and $a_\nu^L(C^{+2})$ is the L-shell photoionization cross section for C^{+2}, with threshold frequency ν_L. Beyond $h\nu_L = 47.9$ eV, there is very little photospheric or diffuse radiation at the effective temperatures of B stars, so J_ν can be replaced by J_ν^x. Furthermore, C^{+4} is produced mainly by Auger ionization of C^{+2} and destroyed by recombination into C^{+3}, giving

$$n_e n(C^{+4})\alpha(C^{+3}) = n(C^{+2})\int_{\nu_K}^{\infty}\frac{4\pi}{h\nu}a_\nu^K(C)J_\nu^x\,d\nu. \quad (10)$$

Combining equations (9) and (10), we obtain

$$g(C^{+3}) = \frac{n(C^{+3})}{n(C^{+2})} = \frac{\int_{\nu_K}^{\infty}\frac{4\pi}{h\nu}a_\nu^K(C)J_\nu^x\,d\nu + \int_{\nu_L}^{\infty}\frac{4\pi}{h\nu}a_\nu^L(C^{+2})J_\nu^x\,d\nu}{n_e\alpha(C^{+2})} \quad (11)$$

for the case of a strong diffuse field. We see that Auger ionization of C^{+2} indirectly populates C^{+3} through recombination of C^{+4}. Taking the ratio of equation (11) with $g(C^{+3})$ from equation (1) for no diffuse radiation, we get

$$\frac{[g(C^{+3})n_e]_{\rm with\ diffuse}}{[g(C^{+3})n_e]_{\rm without\ diffuse}} = 1 + \frac{\int_{\nu_L}^{\infty}\frac{4\pi}{h\nu}a_\nu^L(C^{+2})J_\nu^x\,d\nu}{\int_{\nu_K}^{\infty}\frac{4\pi}{h\nu}a_\nu^K(C)J_\nu^x\,d\nu}. \quad (12)$$

This shows that Auger ionization produces C^{+3} at a rate which is independent of the diffuse field strength, i.e., independent of whether C^{+1} or C^{+2} is dominant. In the case that C^{+2} is dominant, there is some additional production of C^{+3} by outer-shell ionization of C^{+2}. This accounts for the small differences between the C^{+3} abundances listed in Table 1. Note that the right-hand side of equation (12) depends only on atomic parameters and the frequency dependence of J_ν^x. Since we assume the same X-ray source temperature for all B supergiants, this frequency dependence does not change from star to star. For $T_s = 2\times10^6$ K, the right-hand side of equation (12) has a value of 1.4. The C^{+3} abundance ratios given in Table 1 are even closer to unity than 1.4. This is because the presence of a diffuse field increases the degree of ionization of helium and hence increases the electron density (which appears on the left-hand side of eq. [12]).

The ionization equilibrium calculations for silicon are more complicated than those for carbon because the abundant Si^{+1} and Si^{+2} ions have more than 10 electrons. For these ions, K-shell absorption of an X-ray photon results in the ejection of three or four electrons, absorption by the $2s$ subshell of Si^{+1} ejects three electrons, and two electrons are ejected following X-ray absorption by the Si^{+1} $2p$ and Si^{+2} $2s$ and $2p$ subshells (Weisheit 1974). Our calculations show that the rates for processes which eject three or four electrons are at least 5 times smaller than for those which eject two. This is because the absorption cross sections are smaller for energy levels that lie deeper in the ion. Thus we can consider only those L-shell absorptions which eject two electrons. Since corresponding ion stages of silicon and carbon have similar electronic configurations (e.g., Si^{+1} $3s^23p$ and C^{+1} $2s^22p$), L-shell ionization of Si^{+1} or Si^{+2} is equivalent to K-shell ionization of C^{+1} or C^{+2}. As for the case of carbon, L-shell ionization of Si^{+1} produces Si^{+3} directly and L-shell ionization of Si^{+2} indirectly populates Si^{+3} through recombination of Si^{+4}. Thus, Auger ionization produces Si^{+3} at a rate which is independent of the relative Si^{+1} and Si^{+2} abundances, i.e., independent of diffuse field strength. Since outer-shell X-ray ionization of Si^{+2} is unimportant compared to Auger ionization in producing Si^{+3}, we have

$$\frac{[g(\mathrm{Si}^{+3})n_e]_{\text{with diffuse}}}{[g(\mathrm{Si}^{+3})n_e]_{\text{without diffuse}}} \approx 1. \qquad (13)$$

For supergiants later than B2.5, the Si^{+3} abundance ratios in Table 1 are slightly less than unity because of the dependence of electron density on diffuse field strength. For earlier spectral types, the Si^{+3} abundance is sensitive to the strength of the diffuse field because diffuse radiation beyond 33.5 eV becomes important in the production of Si^{+3} by outer-shell ionization of Si^{+2}.

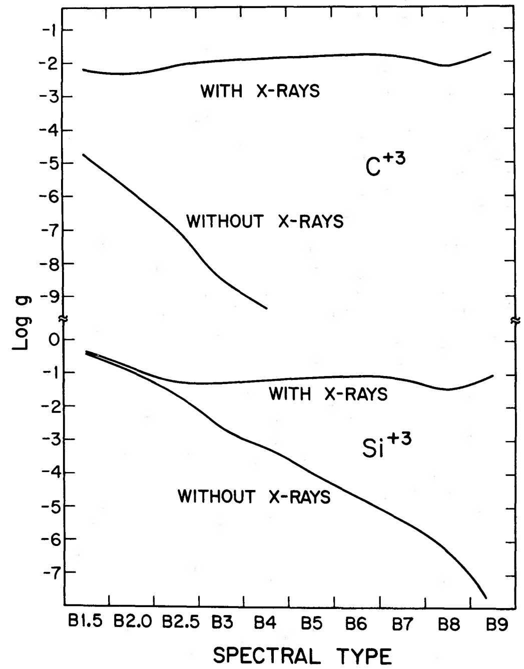

FIG. 1.—Sensitivity of C^{+3} and Si^{+3} abundances to X-ray emission as a function of spectral type. The upper curve for each ion was calculated assuming $L_x = 10^{-7.5}\, L_{\rm bol}$; the lower curve, assuming no X-ray emission. The Si^{+3} abundance is seen to be nearly independent of X-ray luminosity for supergiants earlier than B3, and therefore is useful as an X-ray diagnostic only for later type stars.

c) The Sensitivity of Ion Abundances to X-ray Luminosity

We have seen that the Si IV lines are good diagnostics of X-ray luminosity in supergiants from B3 to B9 and the C IV lines are good diagnostics from B1.5 to B9. Over these ranges in spectral type, X-ray ionization is important in producing both of these ions and their abundances are nearly independent of the strength of the diffuse radiation field. Figure 1 shows the dependence of C^{+3} and Si^{+3} abundance on X-ray emission. For each ion, the upper curve is for an X-ray luminosity $L_x = 10^{-7.5} L_{\rm bol}$ and the lower curve is for no X-ray emission. A strong diffuse radiation field has been assumed in both cases. The Si^{+3} abundance becomes rather independent of X-ray luminosity for supergiants earlier than B3 because ionization of Si^{+2} by the photospheric and diffuse radiation dominates over X-ray ionization in producing Si^{+3}. The C^{+3} abundance is sensitive to X-ray luminosity throughout the range from B1.5 to B9 because C^{+2} has a higher ionization potential than Si^{+2} and is therefore not ionized by the photospheric and diffuse radiation.

For deriving estimates of X-ray luminosity, we use observed Si IV line strengths for stars from B3 to B9 and C IV line strengths from B1.5 to B6. Beyond B6, the absence of C IV lines is used to obtain upper limits to X-ray luminosity.

IV. ANALYSIS OF ULTRAVIOLET LINE OBSERVATIONS

We have chosen to derive the fractional abundances of C^{+3} and Si^{+3} by using the line profile analysis of Olson (1978). Olson calculated profiles for the case of the "standard velocity law" used in our calculations and for several values of the exponent β which describes the run of fractional ion abundance with radius, $g \propto r^{\beta}$. So, for example, if $\beta = -2$, the abundance decreases in the outward direction. For each value of β (-4, -2, 0, and $+2$), Olson calculated a family of P Cygni profiles. The strength is parameterized by a quantity α which is related to the optical depth in the line.

We obtained values of α for the C IV λ1548, Si IV λ1394, and Si IV λ1403 lines for the 20 stars in the Cassinelli and Abbott (1981) *International Ultraviolet Explorer* survey. The β value was estimated from the line shape, and then α was determined from the measured residual intensity at $v = 0.7\ v_{\infty}$ shortward of line center. With the velocity law we are using (eq. [8]), this corresponds to a radial distance $r = 2R_*$. Also, at this position in the C IV λ1548 line, there is no possibility of extra absorption by C IV λ1551 in any of the stars. This would only be a problem if the terminal velocity were greater than about 1650 km s^{-1}. The terminal velocity we used for each star is given in Table 2 and was obtained from either N V λ1239, C IV λ1548, Si IV λ1394, or Si IV λ1403, whichever gave the largest value.

With the derived value of α, the ion abundance is given by

$$g_{\rm obs} = \alpha \left[\lambda_0 f A_E \left(\frac{\dot{M}}{10^{-6}\ M_\odot\ {\rm yr}^{-1}} \right) \times \frac{R_\odot}{R_*} \left(\frac{1000\ {\rm km\ s}^{-1}}{v_\infty} \right)^2 \right]^{-1}, \qquad (14)$$

from Olson (1978). Here λ_0 is the rest wavelength of the line in microns, f is the oscillator strength, and A_E is the elemental abundance relative to hydrogen. Values of $\lambda_0 f A_E$ for each line were tabulated by Olson. The stellar radii and mass loss rates used for each star are listed in Table 2. For the mass loss rates, we have used an expression derived from radio observations of luminous stars by Abbott *et al.* (1980). They found

$$\dot{M} = 1.4 \times 10^{-16} (L/L_\odot)^{1.8}\ M_\odot\ {\rm yr}^{-1}, \qquad (15)$$

which gives a reasonably good fit to the average of the rates derived from infrared observations by Barlow and Cohen (1977) and from the ultraviolet analysis of Garmany *et al.* (1981). To study the effects of uncertainties in $\dot{M}$, we have also used mass loss rates which are both larger and smaller than those given by equation (15). This is discussed in § V.

Our values of β, $\log \alpha$, and $\log g_{\rm obs}$ for each line are given in Table 3. For some of the later B supergiants, the lines were rather weak and blended and showed negligible P Cygni shape. Upper limits to the observed abundances were derived in these cases, assuming $\beta = -2$. Also, the C IV λ1548 line appeared saturated in the B2 stars 9 Cep and 10 Per. For saturated lines, the profile is independent of β, so only lower limits to the abundances were obtained.

V. DERIVED X-RAY LUMINOSITIES

Using the stellar parameters given in Table 2, we can calculate the C^{+3} and Si^{+3} abundances in the wind of each star if the X-ray source emission measure EM_s is specified. Conversely, the observed ion abundances obtained in the previous section can be used to determine the emission measure for each star. We assume an initial value of the emission measure to calculate the abundances of C^{+3} and Si^{+3} at $r = 2R_*$. An adjusted emission measure is then determined using the observed abundance from each spectral line, with

$$EM_s = (g_{\rm obs}/g_{\rm calc}) \times EM_s({\rm assumed}). \qquad (16)$$

This assumes the ion abundance to be directly proportional to the source emission measure (i.e., to the X-ray luminosity). We have shown this to be the case for C^{+3} in § III, but it is not strictly true for Si^{+3} because X-ray ionization is not always the only important means of producing Si^{+3}. For this reason, it was necessary to carry the procedure through two iterations, so that the final EM_s value derived from each Si IV line was close to the value from the first iteration. From each derived value for the source emission measure, the X-ray luminosity in the *Einstein Observatory* IPC bandpass is calculated using

$$L_x = \int EM_s \Lambda_\nu(T_s)\, d\nu. \qquad (17)$$

The results of our calculations are presented in Table 4. For each star later than B2.5, the observed abundances obtained from the three spectral lines give three separate estimates of X-ray luminosity. Only the C^{+3} abundance is used for stars of spectral type B2.5 and earlier because, as we have seen from Figure 1, the Si^{+3} abundance is not a good X-ray diagnostic for these stars. The assumed emission measure given in Table 4 is the result of our first iteration. The calculations have been made assuming no diffuse radiation field and an X-ray source temperature of 2×10^6 K.

TABLE 3

Observed Line Strengths

Star	C IV λ1548			Si IV λ1394			Si IV λ1403		
	β	log α	log g	β	log α	log g	β	log α	log g
HD 106343	−2	−9.08	−2.06	0	−9.68	−2.04	0	−10.00	−2.06
χ^2 Ori	−2	−9.57	−2.90	−2	−10.01	−2.73	−2	−10.20	−2.61
10 Per...........	0	> −9.43	> −2.43	0	−9.62	−2.01	−2	−9.46	−1.55
θ Ara	0	−9.96	−2.82	0	−10.32	−2.56	0	−10.47	−2.41
9 Cep	0	> −9.43	> −2.12	−2	−9.43	−1.51	0	−9.92	−1.70
HD 92964	−1	−9.62	−2.70	−2	−9.72	−2.28	−2	−9.55	−1.66
HD 116084	−1	−9.18	−1.48	−2	−9.36	−1.05	0	−9.57	−0.96
3 Gem	−1	−9.31	−1.64	−2	−9.54	−1.25	0	−10.04	−1.45
55 Cyg	0	−9.43	−2.29	0	−9.43	−1.68	−2	−9.49	−1.44
HD 75149	−1	−10.28	−3.09	0	−9.96	−2.11	−2	−9.60	−1.45
HD 79186	0	−10.00	−2.65	−2	−9.49	−1.53	−2	−9.72	−1.46
η CMa	−2	−10.09	−3.10	−2	−9.92	−2.32	−2	−10.51	−2.61
ϕ Vel	0	−10.01	−2.28	−2	< −10.00	< −1.65	−2	< −10.40	< −1.75
67 Oph...........	−2	−9.85	−2.07	−2	< −10.00	< −1.60	−2	< −10.00	< −1.30
HD 74371	0	−9.68	−2.21	0	−9.70	−1.60	−1	−9.84	−1.51
HD 125288	−2	< −10.40	< −2.48	−2	< −10.10	< −1.56	−2	< −10.40	< −1.56
HD 91619	−2	< −10.40	< −3.10	0	−9.95	−2.04	−2	−10.29	−2.08
β Ori	−2	< −10.10	< −3.35	−2	−9.70	−2.34	−2	−9.96	−2.30
HD 46769	−2	< −10.57	< −3.17	−2	< −10.40	< −2.39	−2	< −10.57	< −2.25
σ Cyg	−2	< −10.40	< −2.87	−2	−9.43	−1.29	−2	< −10.00	< −1.55

Final derived X-ray luminosities are shown in Figure 2 along with the results for B stars from the *Einstein Observatory* IPC survey of Cassinelli *et al.* (1981). The stars observed with the IPC are shown by name. The late O supergiants and early B supergiants have observed $L_x/L_{\rm bol} \approx 10^{-7.2}$. There is some trend seen in the IPC results for a decrease in $L_x/L_{\rm bol}$ with later spectral type. Only upper limits were found for stars later than θ Ara (B2 Ib). Our values of $L_x/L_{\rm bol}$ determined from C IV λ1548 line strengths are shown with filled squares. Those determined from the Si IV λ1394 and Si IV λ1403 line strengths are shown with filled circles. For stars with very weak or absent spectral lines, the upper limits obtained for the observed abundances gave upper limits to X-ray luminosity. Lower limits to X-ray luminosity were obtained for stars with saturated C IV profiles. Figure 2 shows a general trend for $L_x/L_{\rm bol}$ to decrease toward later spectral type, from $10^{-7.2}$ for early B supergiants to about $10^{-8.5}$ for B supergiants later than B6. There are no systematic differences in $L_x/L_{\rm bol}$ between luminosity classes Ia and Ib.

Our estimate of L_x for θ Ara is below the detected value by a factor of about 2.5, suggesting that X-ray luminosities obtained from a single spectral line are good to roughly half an order of magnitude. Also, our results from the three spectral lines for each star later than B2.5 generally agree within a factor of 3 or less. Most of the uncertainty here is probably due to uncertainty in the line parameter β. Errors in β of ± 2 are quite possible and can introduce an error in the X-ray luminosity derived from a single spectral line, up to a factor of 3 for a strong line. For this reason, β was estimated separately for each line, even though the true value of β must be the same for the two Si IV lines. For each star of spectral type B3 or later, the average of the L_x values derived from the three spectral lines should not be greatly affected by errors in β.

We have checked to see if our derived X-ray luminosities are sensitive to the value assumed for the X-ray source temperature T_s. Cassinelli *et al.* (1981) made calculations of the ionization equilibrium of carbon for several different values of T_s. Their results show that, for $T_s = 10^6$ K, the X-ray luminosities derived from the C IV lines would increase by at most a factor of 3.5, and for $T_s = 5 \times 10^6$ K, they would increase by at most 1.5. The derived luminosities increase in both cases because the total emissivity at frequencies above the K-shell edge of carbon (at λ = 42 Å) peaks near $T_s = 2 \times 10^6$ K (see Raymond, Cox, and Smith 1976). We can conclude that any variation in X-ray source temperature with spectral type would not strongly affect the large decrease found for $L_x/L_{\rm bol}$.

We have also investigated the dependence of derived X-ray luminosity on the mass loss rate $\dot{M}$ used in our calculations. The value of L_x derived from either C^{+3} or Si^{+3} depends on the ratio of $g_{\rm calc}$ to $g_{\rm obs}$ (eqs. [16] and [17]). We see from equation (14) that the observed C^{+3} and Si^{+3} abundances are inversely proportional to $\dot{M}$. If the C^{+2} and Si^{+2} abundances are negligible, then the calculated C^{+3} and Si^{+3} abundances are also inversely proportional to $\dot{M}$, as in equation (5). In this case, the mass loss rate cancels in the calculation of X-ray

TABLE 4

DERIVED X-RAY LUMINOSITIES

STAR	UV LINE[a]	ASSUMED log EM_s	CALCULATED log g	OBSERVED log g	DERIVED PARAMETERS log EM_s	DERIVED PARAMETERS L_x(ergs s^{-1})	DERIVED PARAMETERS log L_x/L_{bol}
HD 106343 ...	C IV	54.23	−2.20	−2.06	54.37	3.8×10^{31}	−7.36
χ^2 Ori	C IV	54.44	−2.36	−2.90	53.90	1.3×10^{31}	−8.04
10 Per	C IV	54.35	−2.01	> −2.43	> 53.93	$>1.4\times10^{31}$	> −7.77
θ Ara	C IV	53.13	−3.19	−2.82	53.50	4.7×10^{30}	−8.13
9 Cep	C IV	54.02	−1.87	> −2.12	> 53.77	$>9.4\times10^{30}$	> −7.65
HD 92964	C IV	53.51	−2.70	−2.70	53.51	5.1×10^{30}	−8.10
HD 116084 ...	C IV	54.07	−1.32	−1.48	53.91	1.3×10^{31}	−7.26
3 Gem	C IV	53.81	−1.62	−1.64	53.79	9.8×10^{30}	−7.42
55 Cyg	C IV	54.03	−1.97	−2.29	53.71	8.1×10^{30}	−7.82
	Si IV[1]	54.03	−1.30	−1.68	53.65	7.1×10^{30}	−7.88
	Si IV[2]	54.03	−1.30	−1.44	53.89	1.2×10^{31}	−7.64
HD 75149	C IV	53.25	−2.54	−3.09	52.70	8.1×10^{29}	−8.70
	Si IV[1]	53.25	−1.83	−2.11	52.97	1.5×10^{30}	−8.43
	Si IV[2]	53.25	−1.83	−1.45	53.63	6.9×10^{30}	−7.77
HD 79186	C IV	53.32	−2.33	−2.65	53.00	1.6×10^{30}	−8.32
	Si IV[1]	53.32	−1.61	−1.53	53.40	4.0×10^{30}	−7.92
	Si IV[2]	53.32	−1.61	−1.46	53.47	4.7×10^{30}	−7.85
η CMa	C IV	52.31	−3.61	−3.10	52.82	1.0×10^{30}	−8.59
	Si IV[1]	52.31	−2.86	−2.32	52.85	1.1×10^{30}	−8.56
	Si IV[2]	52.31	−2.86	−2.61	52.56	5.6×10^{29}	−8.85
ϕ Vel	C IV	52.46	−2.56	−2.28	52.74	8.7×10^{29}	−8.22
	Si IV[1]	52.46	−1.85	< −1.65	< 52.66	$<7.3\times10^{29}$	< −8.30
	Si IV[2]	52.46	−1.85	< −1.75	< 52.56	$<5.8\times10^{29}$	< −8.40
67 Oph	C IV	53.44	−1.54	−2.07	52.91	1.2×10^{30}	−8.03
	Si IV[1]	53.44	−0.88	< −1.60	< 52.72	$<7.8\times10^{29}$	< −8.22
	Si IV[2]	53.44	−0.88	< −1.30	< 53.02	$<1.6\times10^{30}$	< −7.92
HD 74371	C IV	53.12	−2.36	−2.21	53.27	3.0×10^{30}	−7.95
	Si IV[1]	53.12	−1.63	−1.60	53.15	2.2×10^{30}	−8.07
	Si IV[2]	53.12	−1.63	−1.51	53.24	2.8×10^{30}	−7.98
HD 125288 ...	C IV	52.27	−2.47	< −2.48	< 52.26	$<3.0\times10^{29}$	< −8.51
	Si IV[1]	52.27	−1.69	< −1.56	< 52.40	$<4.1\times10^{29}$	< −8.37
	Si IV[2]	52.27	−1.69	< −1.56	< 52.40	$<4.1\times10^{29}$	< −8.37
HD 91619	C IV	52.64	−2.96	< −3.10	< 52.50	$<5.0\times10^{29}$	< −8.74
	Si IV[1]	52.64	−2.21	−2.04	52.81	1.0×10^{30}	−8.43
	Si IV[2]	52.64	−2.21	−2.08	52.77	9.4×10^{29}	−8.47
β Ori	C IV	52.93	−3.13	< −3.35	< 52.71	$<8.3\times10^{29}$	< −8.72
	Si IV[1]	52.93	−2.36	−2.34	52.95	1.4×10^{30}	−8.48
	Si IV[2]	52.93	−2.36	−2.30	52.99	1.6×10^{30}	−8.44
HD 46769	C IV	52.05	−2.73	< −3.17	< 51.61	$<6.5\times10^{28}$	< −8.94
	Si IV[1]	52.05	−1.96	< −2.39	< 51.62	$<6.6\times10^{28}$	< −8.93
	Si IV[2]	52.05	−1.96	< −2.25	< 51.76	$<9.1\times10^{28}$	< −8.79
σ Cyg	C IV	52.38	−2.74	< −2.87	< 52.25	$<2.8\times10^{29}$	< −8.63
	Si IV[1]	52.38	−1.97	−1.29	53.06	1.8×10^{30}	−7.82
	Si IV[2]	52.38	−1.97	< −1.55	< 52.80	$<1.0\times10^{30}$	< −8.08

[a] C IV = C IV λ1548; Si IV[1] = Si IV λ1394; Si IV[2] = Si IV λ1403.

luminosity. This is also approximately true if C^{+2} and Si^{+2} are present in significant amounts. As discussed in § III in regard to equation (12), Auger ionization produces C^{+3} and Si^{+3} at rates which are independent of the relative populations of the second and third ion stages. Since outer-shell ionization of C^{+2} and Si^{+2} is less efficient in producing C^{+3} and Si^{+3} than Auger ionization is, any change of the C^{+2} or Si^{+2} abundance with mass loss rate results in only a small change in the total C^{+3} or Si^{+3} production rate. Thus, we expect the calculated abundances of these ions to vary with $\dot{M}$ approximately as the observed abundances do, and the derived luminosities should not be very sensitive to mass loss rate.

To check this, we have repeated our ionization calculations for several B supergiants using different mass loss rates. With mass loss rates which are a factor of 2 lower than our adopted values from equation (15), the derived X-ray luminosities were found to decrease by at most 30%. At the lower electron densities, the recombination rates are lower and there is less attenuation of the photospheric radiation, both of which cause the C^{+2}

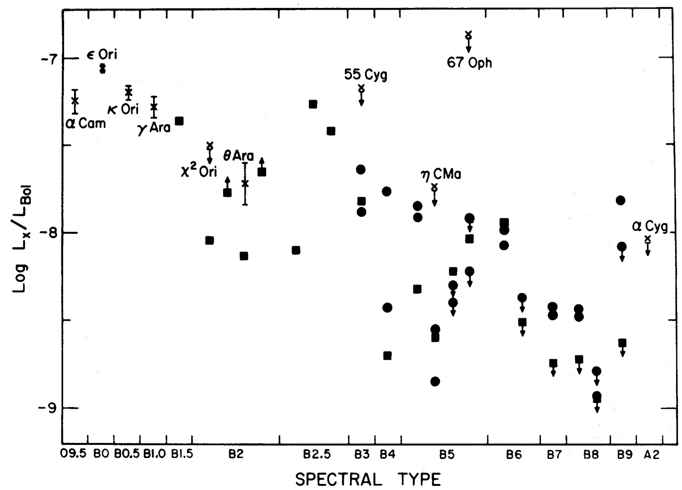

FIG. 2.—Ratio of X-ray luminosity to bolometric luminosity as a function of spectral type. Results of *Einstein Observatory* IPC observations are shown with an × and labeled by the star name. Values of $L_x/L_{\rm bol}$ derived from C IV λ1548 observations are shown with filled squares. Those from Si IV λ1393 and Si IV λ1403 observations are shown with filled circles.

and Si^{+2} abundances to be larger. Because of increased outer-shell ionization, the calculated C^{+3} and Si^{+3} abundances increase by somewhat more than the factor of 2, so the derived X-ray luminosities decrease slightly.

Similarly, using mass loss rates larger than our adopted values results in only a small increase in X-ray luminosity. Chiosi and Olson (1982) have suggested that mass loss rate depends on the effective gravitational potential at the stellar surface in addition to luminosity. Using their two-parameter relationship for mass loss rate, values of $\dot{M}$ were obtained which range from about 3 times larger than our adopted values for early B supergiants to about 6 times larger for late B supergiants. Our calculations made with these higher mass loss rates for several stars gave an increase of less than 5% in derived X-ray luminosity in all cases. This is because the C^{+2} and Si^{+2} abundances calculated with our adopted mass loss rates were already quite low, so outer-shell ionization of these ions was already of low importance in producing C^{+3} and Si^{+3}.

Our initial calculations with the larger mass loss rates indicated that hydrogen would be largely neutral at two stellar radii. However, there are reasons to doubt that this can be the case. The large values of $\dot{M}$ obtained for B supergiants by Barlow and Cohen (1977), on which the relation given by Chiosi and Olson (1982) was based, were from infrared observations of excess free-free emission and hence refer to outflow of ionized gas. Also, if hydrogen were neutral, charge transfer reactions of C^{+3} and Si^{+3} with H^0 would be very efficient in depopulating these high ion stages. At a wind temperature of 10^4 K, for example, the recombination rate coefficients of C^{+3} to C^{+2} and Si^{+3} to Si^{+2} by charge transfer are about 1000 times and 100 times larger, respectively, than the corresponding rate coefficients for radiative plus dielectronic recombination (Butler and Dalgarno 1980; Aldrovandi and Péquignot 1973). Thus, if a significant amount of hydrogen were neutral, the observed C IV and Si IV line strengths would imply very high X-ray luminosities—very much larger than the upper limits from the IPC observations of Cassinelli *et al.* (1981). For these reasons we have assumed hydrogen to be completely ionized in our calculations. Felli and Panagia (1982) have considered the ionization of extended envelopes around stars for the general case of an accelerating outflow. For B supergiants, they found the stellar Lyman-continuum flux given by model atmospheres to be insufficient to account for the envelope ionization indicated by radio and infrared observations. They suggested that the ionization is due to a moderate flux excess in the far-ultraviolet. The presence of such an ultraviolet excess would not significantly change the X-ray luminosities obtained in this paper, its effects being similar to those of a strong diffuse radiation field, which were discussed in § III.

VI. CONCLUSION

We have considered some of the problems related to deriving X-ray luminosities from observations of lines from Auger enhanced ions. We have found that the ion N^{+4} is not useful in the B spectral range because it is very sensitive to the diffuse radiation field. In contrast, the C IV and Si IV line strengths are excellent diagnostics of X-ray luminosity, being only slightly affected by the diffuse field. For all three elements, the diffuse field strength determines the relative populations of the second and third ion stages, which are the most abundant stages in the winds of B supergiants. The C^{+3} and Si^{+3} ions are produced by Auger ionization of either of these stages, but N^{+4} is produced by Auger ionization of only one of them (N^{+2}). Thus the N^{+4} line strengths are strongly dependent on the diffuse radiation field.

For our ion abundance calculations, the X-ray radiation field was assumed to be like that observed in early B supergiants and mass loss rates have been estimated using an extrapolation of radio observations of earlier OB supergiants. With these assumptions, X-ray luminosities have been derived which are consistent with the available *Einstein Observatory* results. The derived X-ray luminosities show as a general trend that L_x decreases from $10^{-7.2}$ L_{bol} for early B supergiants to about $10^{-8.5} L_{bol}$ for B supergiants later than B6. This large decrease in X-ray luminosity is not very sensitive to our assumed X-ray source temperature or to our adopted mass loss rates.

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REFERENCES

Abbott, D. C. 1978, *Ap. J.*, **225**, 893.
Abbott, D. C., Bieging, J. H., Churchwell, E., and Cassinelli, J. P. 1980, *Ap. J.*, **238**, 196.
Aldrovandi, S. M. V., and Péquignot, D. 1973, *Astr. Ap.*, **25**, 137.
Barlow, M. J., and Cohen, M. 1977. *Ap. J.*, **213**, 737.
Butler, S. E., and Dalgarno, A. 1980, *Ap. J.*, **241**, 838.
Cassinelli, J. P., and Abbott, D. C. 1981, in *The Universe at Ultraviolet Wavelengths: The First Two Years of IUE*, ed. R. D. Chapman (NASA Conference Publication 2171), p. 127.
Cassinelli, J. P., and Olson, G. L. 1979. *Ap. J.*, **229**, 304 (CO).
Cassinelli, J. P., and Swank, J. H. 1982, in preparation.
Cassinelli, J. P., Waldron, W. L., Sanders, W. T., Harnden, F. R., Jr., Rosner, R., and Vaiana, G. S. 1981, *Ap. J.*, **250**, 677.
Chiosi, C., and Olson, G. L. 1982, in preparation.
Felli, M., and Panagia, N. 1982, *Astr. Ap.*, in press.
Garmany, C. D., Olson, G. L., Conti, P. S., and Van Steenberg, M. 1981, *Ap. J.*, **250**, 660.
Humphreys, R. M. 1978. *Ap. J. Suppl.*, **38**, 309.
Klein, R. I., and Castor, J. I. 1978, *Ap. J.*, **220**, 902.
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Lesh, J. R. 1968, *Ap. J. Suppl.*, **17**, 371.
Long, K. S., and White, R. L. 1980, *Ap. J. (Letters)*, **239**, L65.
Lucy, L. B., and White, R. L. 1980, *Ap. J.*, **241**, 300.
Morton, D. C. 1979, *M.N.R.A.S.*, **189**, 57.
Olson, G. L. 1978, *Ap. J.*, **226**, 124.
Olson, G. L., and Castor, J. I. 1981, *Ap. J.*, **244**, 179.
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976. *Ap. J.*, **204**, 290.
Raymond, J. C., and Smith, B. W. 1979, private communication.
Rosendhal, J. D. 1973, *Ap. J.*, **182**, 523.
Waldron, W. L. 1982, in preparation.
Weisheit, J. C. 1974, *Ap. J.*, **190**, 735.

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