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OSO-8 X-Ray Observations of AM Herculis

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ABSTRACT

We report the results of hard X-ray observations of the binary system AM Her, which were coincident with soft X-ray and ground-based optical measurements. In the 2-60 keV band, variability was detected with an eclipse during phases 0.5 to 0.7 with respect to the $0^{d}.12892$ period optical minima, synchronous with the known soft X-ray eclipse. The 2-60 keV uneclipsed flux was 9.5×10^{-10} erg cm^{-2} sec^{-1}, of which 86% lies above 10 keV. Thus AM Her contains a hard source located near the similarly eclipsed soft X-ray source. The X-ray data are interpreted in terms of thermal bremsstrahlung from accretion onto a white dwarf.

SUBJECT HEADINGS: stars, U Gem; X-rays, sources

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I. INTRODUCTION

The binary system AM Herculis is known to exhibit a variety of periodic and random phenomena. At optical wavelengths, its spectrum is usually dominated by high excitation emission lines which show radial velocity variations of several hundred km/s with a $0\overset{d}{.}12892$ period (Priedhorsky 1977; Cowley and Crampton 1977). Multicolor photometry has established light curves having primary and secondary minima (Szkody and Brownlee 1977; Berg and Duthie 1977) throughout May 1976 and primary minima alone during November 1976 (Priedhorsky and Krzeminski 1976); in addition, flickering on a time scale of minutes occurs at all phases. Long term photographic surveys (Dexter et al. 1976) suggest a long period on-off behavior with P = 670d. Broadband optical polarization measurements (Tapia 1976a,b; Tapia 1977) show a brief linear polarization event each $0\overset{d}{.}12892$ with an amplitude of several percent, and a high degree of circular polarization, again variable and synchronized with the binary motion. At X-ray wavelengths, the UHURU object 3U1809+50 has been tentatively identified with AM Her by Berg and Duthie (1977); this identification is combatible with the revised UHURU position and with the Ariel V position for 2A1815+500. A soft X-ray source at the position of Am Her has been observed by the SAS-3 group (Hearn et al. 1976a,b; Hearn and Richardson 1977) which shows a periodic intensity variation with orbital phase, with a well-defined minimum at $\phi \simeq 0.1$ with respect to the linear polarization maximum. There is an increasing volume of evidence that these "periodic" phenomena are themselves variable; for instance, the linear polarization events are substantially less pronounced in 1977 than in

1976 (Tapia 1977, private communication).

In this letter we report the OSO-8 observations of AM Her which were conducted 11-12 October 1975, when the system was observed for $0^d.73$ by the GSFC 2-60 keV and U. Wisconsin 0.15-25 keV X-ray experiments. This time interval is sufficient for nearly complete coverage of the binary period in spite of the $0^d.062$ period of the spacecraft orbit. Accordingly we are able to construct light curves of AM Her in the energy bands of these experiments. The fact that the AM Her binary period clearly emerges from these data conclusively establishes that AM Her is the hard X-ray source. The high energy (> 2 keV) data are of particular interest because they set a lower limit to the temperature of the emitting region, or alternatively establish, for the first time, the presence of an energetic nonthermal component within the AM Her system.

II. ANALYSIS OF TIMING DATA

The GSFC OSO-8 X-ray experiment has been described previously (Serlemitsos et al. 1976; Pravdo et al. 1976). Data on AM Her were collected using detector A, a xenon-filled proportional counter which views a 5° FWHM circular patch of sky offset 175° from the spacecraft spin axis. To remove the effects of spacecraft rotation and spin axis motion, the background count rates were first determined from off-source portions of each rotation and subtracted. The resulting count rates were then corrected with an exposure factor determined from the known position of AM Her and the spacecraft aspect. The corrected data were combined by a weighted average into 1000s intervals. Light curves for the 2-60 keV and 10-60 keV bands were constructed by folding these means at the known optical period. A convincing level of modulation is seen in both energy bands (see Figure 1) with an essentially complete eclipse centered at JD = 2442696.977, which is at phase 0.58 with respect to the primary B-band optical minimum measured that same night (Berg, private communication 1977). Simultaneous soft X-ray observations by the Wisconsin group (Bunner 1977) reveal that the 0.15-0.28 keV flux has the same temporal behavior as seen at higher energies, with a phase difference not exceeding 0.05 cycles. Polarimetry was not available during our observations, so the phase (or indeed the existence) of a periodic optical polarization pulse is unknown. However, the relative timing of the X-ray and optical minima appears stable: 223 days later, the phase of the SAS-3 minimum with respect to Berg's 1976 photometric minima is 0.59.

III. THE X-RAY SPECTRUM

The GSFC OSO-8 experiment provides 63 channel pulse height distributions accumulated over time intervals corresponding to 0.25 spacecraft rotations. For AM Her these data were grouped into 21 bins and compared with count distributions expected for power law and optically thin thermal bremsstrahlung functions. Background data were obtained from adjacent rotation sectors. The best fitting power law had an energy index of -0.4 and an associated absorption parameter of $N_H = 4 \times 10^{22}$ cm^{-2}. The best fitting bremsstrahlung temperature was 2×10^9 K with N_H = 3×10^{22} cm^{-2}. These spectra are surprisingly hard; about half the observed 2-60 keV energy lies above 28 keV. However, the fit quality is in neither case statistically satisfactory. The models give

$\chi^2 = 35$ and 36, respectively, for 18 degrees of freedom, indicating that the spectrum is more complex than these simple models. Complicated X-ray spectra are theoretically expected in geometries having appreciable stellar X-ray albedo contributions. For example, the albedo calculations of Feldsteiner and Opher (1976) indicate that about 30% of the X-rays intercepted by a star will be reemitted after modification by multiple Compton scattering, atomic fluorescence, and photoelectric absorption.

The 2-60 keV energy flux, averaged over the entire light curve, was 7.6×10^{-10} erg cm^{-2} sec^{-1}. Essentially none of this flux arrives during phases 0.5-0.7. Our time averaged 2-6 keV flux, 5.2×10^{-11} ergs $cm^{-2}s^{-1}$, lies between the 1970-1971 value of 8.7×10^{-11} ergs cm^{-2} s^{-1} (Giacconi et al. 1974) and the 1971-1973 value of 3×10^{-11} ergs $cm^{-2}s^{-1}$ (Murray and Ulmer, 1976) for 3U1809+50. The 2-10 keV flux, 1.05×10^{-10} ergs $cm^{-2}s^{-1}$, is $98 \pm 10\%$ of the 1975 intensity for 2A1815+500 (Cooke et al. 1977).

During the GSFC observations data were also acquired by the Wisconsin soft X-ray experiment. Analysis of these data (Bunner 1977) confirms the presence of the hard component reported above, and establishes the simultaneous presence of a steep spectrum soft component with an intensity of 1.6×10^{-10} ergs $cm^{-2}s^{-1}$ in the 0.19-0.28 keV band. Thus the soft X-ray flux appears to have been several times that measured by SAS-3 (Hearn et al. 1976a,b; Hearn and Richardson 1977) during a low optical state in 1976. The soft flux observed by the Wisconsin experiment is satisfactorily fit by a simple exponential spectrum having kT = .03 keV and an absorption parameter $N_H < 10^{20}$ cm^{-2}, in contrast to the hard flux which, if thermal, has a temperature > 1000 times higher.

The hard and soft X-ray measurements reported here have been plotted in Figure 2, along with Perry's simultaneously acquired V and B photometry (Berg and Duthie 1977). This photometry shows AM Her to have been in its bright state. For contrast we have also indicated the range of optical variability by plotting one of Tapia's (1977) low state UBV measurements, taken 237 days later. The recent infrared measurements by Rieke and Merrill and the optical continuum (see Stockman et. al., 1977) are also shown. From these observations, we note that a substantial amount of the luminosity of AM Her appears in the hard X-ray band: L_x(2-60 keV) = 9.1 x 10^{32} (D/100 pc)^2 erg/sec. The soft X-ray (0.19-0.28 keV), visible (0.3-1μm), and infrared (1-10 μm) bands have respectively 2 x 10^{32}, 1.8 x 10^{32}, and 1.2 x 10^{32} erg/sec at 100 pc distance. Since the X-ray spectrum above 60 keV has not been measured, the total hard X-ray luminosity may considerably exceed the 2-60 keV value. For a thermal bremsstrahlung source with T > 10^9K, the Gaunt factor varies approximately as $(h\nu)^{-0.3}$ and L_x (> 2 keV) = 1.9 x 10^{33} (kT/200 keV)$^{0.7}$ (D/100pc)^2 erg/sec.

IV. DISCUSSION

Models of AM Her have largely been based on the similarity of its optical variability to that of the cataclysmic variable systems, specifically those of the U Geminorum (Bond and Tifft 1974) or Z Camelopardalis type (Berg and Duthie 1977). In such systems material is transferred from a dwarf companion to a degenerate primary star by means of a disk or ring surrounding the latter. Double emission lines characteristic of disks are frequently seen in such systems. Their absence in AM Her can be explained by supposing that light from a single hot spot dominates the emission from the disk (Szkody and Brownlee 1977; Cowley and Crampton 1977) or that the disk is absent and material is transported to the primary in a direct stream (Chanmugam and Wagner 1977; Stockman et al. 1977) which is presumably guided by the magnetic field of the primary. These models also explain the observed emission line radial velocities being maximum at minimum light (Priedhorsky 1977; Cowley and Crampton 1977). The delay of the U-band minimum with respect to the V and R minima can be explained by supposing that the secondary star is hotter towards the primary, so that its light contributes appreciably to the V and R bands, while the hot spot or stream trails the primary (Szkody 1976; Cowley and Crampton 1977; Chanmugam and Wagner 1977). Attempts to model the spectrum and circular polarization of optical continuum have invoked cyclotron emission in a 10^8 gauss field at the surface of the co-rotating primary (Stockman et al. 1977); in this way one may also explain the 7690 Å absorption feature as the quadratic Zeeman turning point of Hα (Angel et al. 1976).

Here, we point out that the hard X-ray emission can be understood in terms of thermal bremsstrahlung radiation from material transferred to the degenerate primary and heated by its infall. Models of this kind have been developed by Hoshi (1973), Aizu (1973), Fabian et al. (1976), and Katz (1977). Near the degenerate primary, we suppose that the accretion flow is magnetically confined to a column of cross sectional area $A = 4\pi R^2 f$ where the radius of the star is $R \simeq 5 \times 10^8 (M_{\odot}/M)$ cm for the Hamada and Salpeter (1971) equation of state. A height h above the primary the material is abruptly heated by a shock and radiates optically thin thermal X-rays for a time interval $4h/V_{freefall}$ before reaching the stellar surface. If $h < R$, the infalling material will be heated to nearly its freefall temperature, $10^9 (M/M_\odot)^2$K. A model of this kind should approximately describe a real flow provided that the total luminosity is low enough to make Compton interactions unimportant (Katz 1977). The model can be made quantitative by adopting some distribution of temperature and density within the shocked material, i.e., for $R < r < R+h$. Following Fabian et al. (1976) we take these functions to be constant. Combining the mass conservation law $\frac{1}{4}\rho A V_{freefall} = \dot{M}$ with the luminosity expression $L = GM\dot{M}/R$, we find for the density of the shocked medium

$$n = 4 \times 10^{12} L_{33} f^{-1} (M/M_\odot)^{-1} \text{ cm}^{-3}. \qquad (1)$$

If bremsstrahlung is to account for the X-ray luminosity L, then the height h of the radiating column must be

$$h = 4.4 \times 10^{11} L_{33}^{-1} f (M/M_\odot)^3 \text{ cm}. \qquad (2)$$

If this model is correct and $kT > 60$ keV, then $M/M_\odot > 0.83$. Since $M/M_\odot$ must be less than Chandrasekhar's limit of 1.40 we adopt $M = M_\odot$ for the primary. From the observed hard energy flux, $L_x \simeq 10^{33} (D/100 \text{ pc})^2$ erg s^{-1}. Hence the column height is $4.4 \times 10^{11} f (D/100 \text{ pc})^{-2}$ cm, which is less than the primary's radius (making the model self-consistent) provided that $f < 10^{-3} (D/100 \text{ pc})^2$. An accretion column occupying this small fraction of the star's surface does not appear to be in conflict with existing accretion theories, especially in view of the extreme ratio of magnetic energy density to gas pressure. For a 1-2 $M_\odot$ system the opening angle of a dipole field line reaching the inner Lagrangian point would be less than 5^{o}, corresponding to an entire polar cap having $f \lesssim 2 \times 10^{-3}$. We further note that the observed optical and soft X-ray fluxes do not cause appreciable Compton cooling of the infalling electrons; hence the bremsstrahlung mechanism for the production of the observed hard X-rays appears justified.

In this model, the observed orbital variation in hard X-ray intensity is due to synchronous rotation of the primary and its occultation of the hot column of material accreting onto it. The height of the column and the inclination of the primary's magnetic pole must combine to give the required X-ray eclipse duration. If $h << R$, about half of the hard radiation is intercepted by the primary, heating it to an effective temperature which depends upon the long term average X-ray production rate and upon the fraction of energy which is thermalized. In any case, $T_{eff} \lesssim 41000\ L_{33}^{1/4}\ (R/5 \times 10^{8})^{-1/2}$ K. This heating could make the primary appear as bright as $m_V \sim 16$ at 100 pc, just below the observed low-state photometric intensity. The combined X-ray and optical radiation from the primary may result in appreciable differential heating of the secondary companion star.

A portion of the hard radiation intercepted by the primary may also be responsible for the soft X-ray emission through the initiation of intense coronal activity on the white dwarf around the accretion column. A corona occupying 10% of the star's area and having a base pressure of $\sim 10^{7}$ (D/100 pc) dyne/cm^2 at 5×10^{5} K would supply the volume emission measure $n_e^2 V = 2 \times 10^{56}$ (D/100 pc)^2 cm^{-3} which we infer from the ¼ keV observations using the radiative cooling calculations of Raymond et al. (1976). This model explains the synchronism and similarity of the hard and soft X-ray orbital light curves, and predicts that the hard and soft fluxes will vary together in response to variations in the accretion flow.

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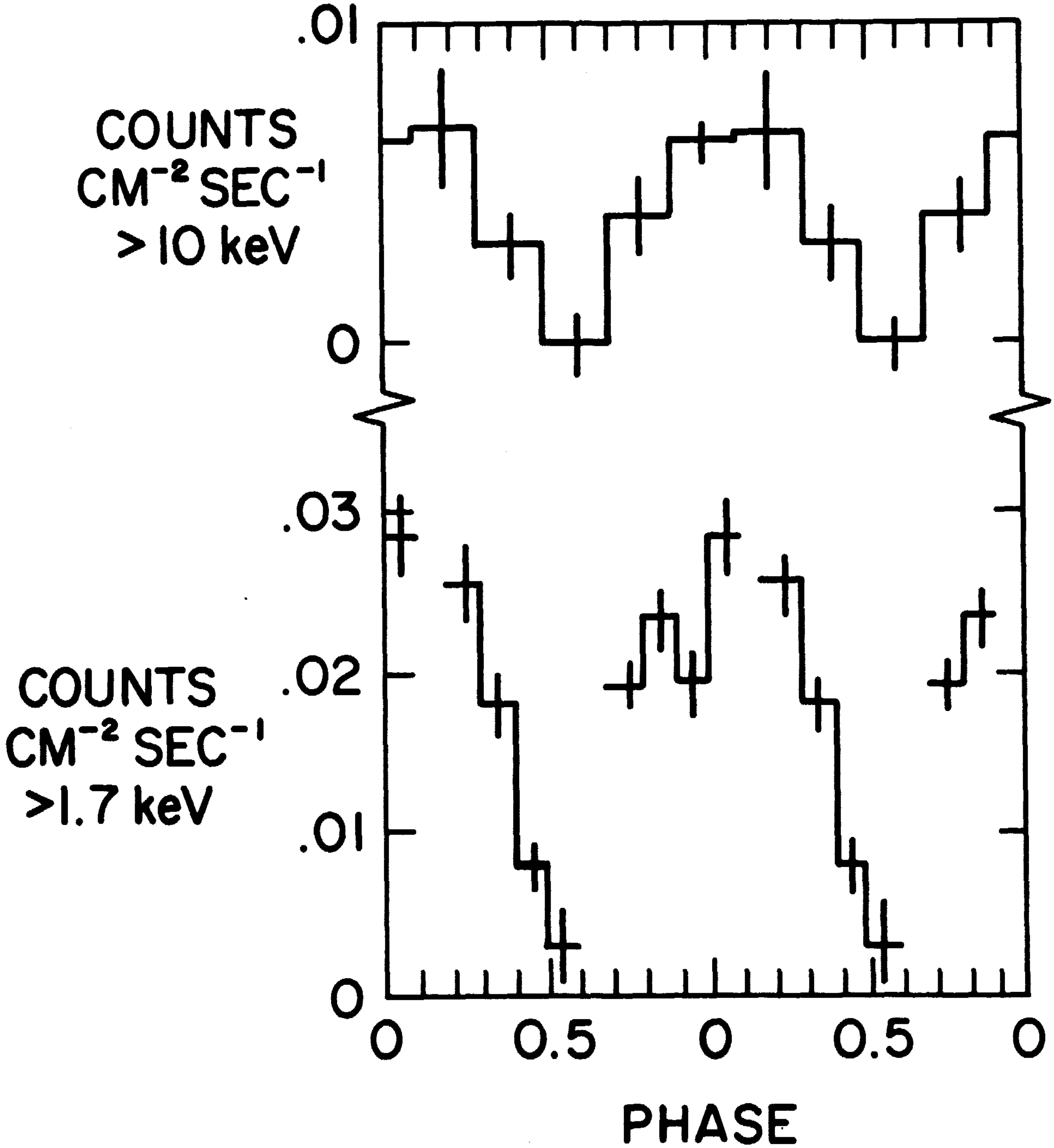
FIGURE CAPTIONS

FIGURE 1 - Light curve for Am Her for 1.7 - 60 keV (lower) and 10 - 60 keV (upper) energy bands, based on an assumed $0^{d}.128926$ period with phase 0.0 at JD2442696.6446 = center of primary optical minimum (Berg, private communication, 1977). The same data are plotted for two cycles.

FIGURE 2 - Observed spectral energy distribution, F_{ν}(erg cm^{-2}sec^{-1} Hz^{-1}). Crosses: data taken 11-12 October 1975, including Wisconsin soft X-ray flux ("W") and optical photometry by Perry ("P"). Noncoincident data are: H, soft X-ray flux by Hearn et al. 1976a; T, UBV photometry by Tapia (1977); S, continuum spectrophotometry by Stockman et al. (1977); M, infrared photometry by Merrill; R, 10.6 m measurement by Rieke (see Stockman et al., 1977).



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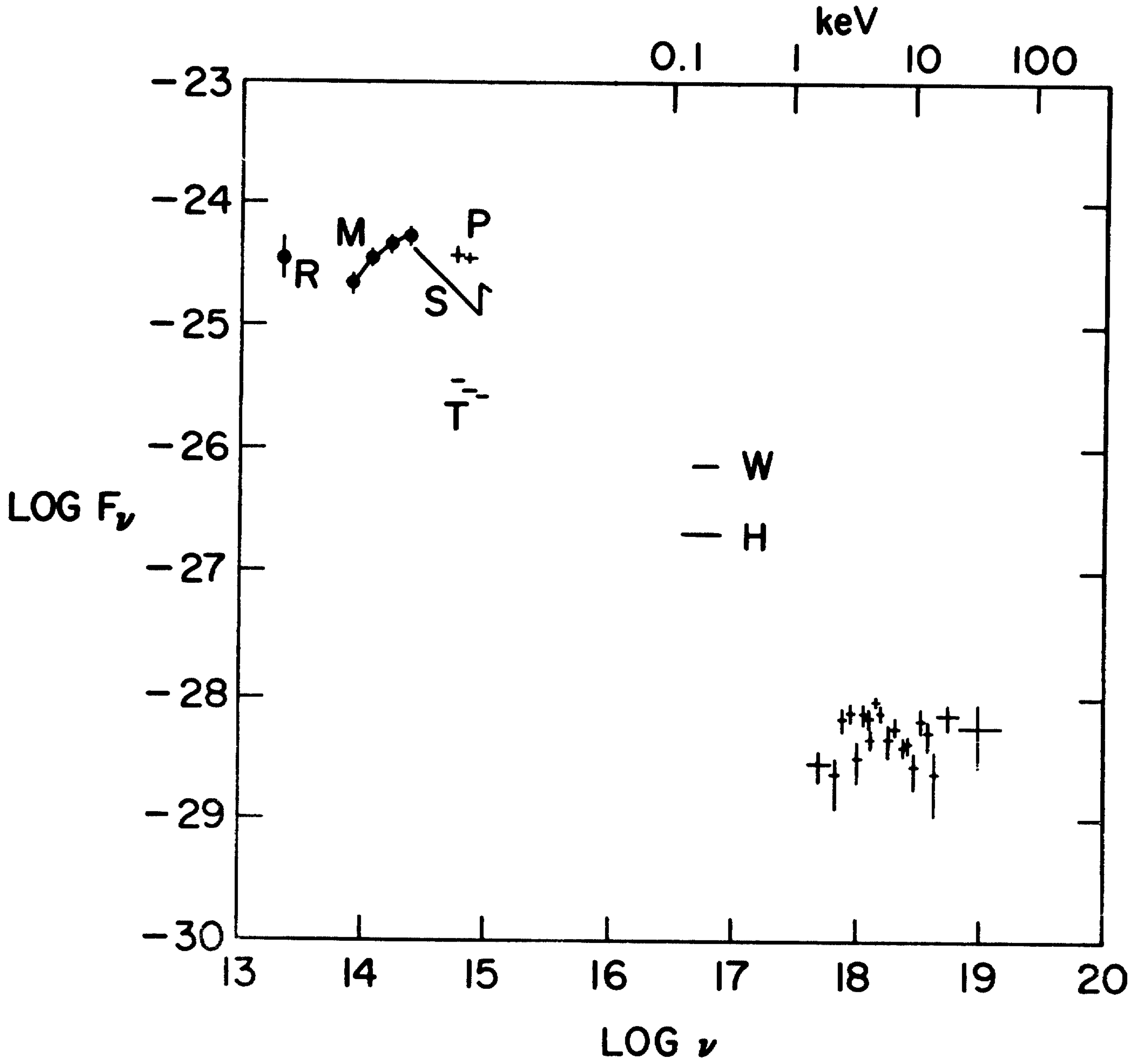
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