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APOLLO-SOYUZ TEST PROJECT

FINAL REPORT

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FINAL REPORT

EXTREME ULTRAVIOLET TELESCOPE
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1. INTRODUCTION

This final report summarizes a number of scientific investigations which have been conducted as follow-on studies to the Apollo-Soyuz Extreme Ultraviolet Telescope experiment, MA-083. These investigations have involved detailed analyses of individual target stars or classes of stars, not only with regard to the EUV data but also in connection with theoretical models and observations in other parts of the spectrum.

Due to the considerable variety of the astrophysical processes associated with the EUVT targets, it has proven fruitful to collaborate with specialists in fields of astrometry, pulsar physics, and flare dynamics. It is for this reason that, in the following discussion, coauthors names appear who are not members of the original Berkeley team. Such collaboration is further evidence of the interest which astronomers are now showing in the new field of extreme ultraviolet astronomy.

2. ANALYSIS OF THE SS CYGNI OBSERVATIONS

The cataclysmic variable star SS Cygni was placed on the EUVT observing schedule because theoretical arguments (summarized below) indicated a potentially intense EUV spectrum, and because in 1974 it was discovered to be a weak soft X-ray emitter. The star was observed during orbits 80, 90, and 105. At these times, ground based optical observers in the U.S. (AAVSO) and in the U.S.S.R. (Lyuty and his coworkers) noted that the star was in its maximum brightness state at about ninth magnitude (at minimum it reaches twelfth magnitude). Our EUV data have now been completely analyzed. The

EUVT detected the star clearly in both the parylene (55 - 150 Å) and beryllium parylene (113 - 150 Å) filter bands. The EUV data thus confirm the basic model for cataclysmic variables, and indeed should allow theoretical formulations of the energy budget of cataclysmic variables to be refined.

The standard model for SS Cygni type systems is a semidetached binary star: a red dwarf releases material from the inner Lagrangian point of the binary system, which is then transferred to a white dwarf companion star by way of an accretion disk. This disk, which surrounds the white dwarf, is the central feature of SS Cygni systems and indeed of all dwarf novae. Within this disk, hot gaseous material orbiting the white dwarf migrates radially inward, transforming gravitational energy into heat and radiation.

The central physical problem connected with all such disks concerns the transport of angular momentum. Fluid models governed by gravity and gas viscosity are not compatible with the mass transfer rates inferred from the present EUV observations. Recently, Dr. R. Mewe of the Space Research Institute of Utrecht has examined our EUV data, and has begun a re-investigation of the angular momentum problem using a mathematical formulation developed by Dr. J. E. Pringle of the Institute of Astronomy at Cambridge, England. Although his investigation is not yet completed, it now appears that the angular momentum barrier can be overcome by mathematical models which incorporate subtle electrodynamic effects such as magnetic viscosity. The application and evaluation of these advanced models has thus been materially advanced by the EUV observations described above.

3. PROXIMA CENTAURI OBSERVATIONS

The red dwarf star Proxima Centauri was observed twice with the Apollo-Soyuz EUVT, on orbits 94 and 109. It was not detected in any of the instrument's bandpasses during the first observation, yet appeared strongly in the 55 - 150 Å band during the second observation. This star has a spectral classification dM5e, and is known to undergo occasional flares. For this reason ground-based optical monitoring has been arranged in advance. Unfortunately a snow storm at the observing site in New Zealand precluded coordinated optical photometry, so we cannot establish the magnitude of the optical flare which presumably was associated with the EUV event. Assuming an optically thin flare at a temperature between 10^6 °K and 10^8 °K, emission measures and luminosities can nonetheless be derived.

Since there exists a scaling theory for stellar flares assuming thermal radiation from a hot plasma as the radiation source, it would be instructive to compare our results to this theory. The main obstacle to this endeavor is represented not surprisingly by the absence of simultaneous optical data. The fundamental parameter to be compared is the ratio L_x/L_{opt}, the X-ray luminosity to the optical luminosity, for the flare. One flare on UV Ceti is unfortunately the only known flare observed simultaneously in the X-ray and the optical and for which an unambiguous determination of L_x/L_{opt} can be made. For Prox Cen we must rely on its past optical flare history to derive L_{opt}. Using this analysis it is found that while observations of UV Ceti and YZ CMi seem to be reasonably compatible with the scaling theory, the ASTP observation of Prox Cen is definitely not. Either the observed EUV flare was an extraordinarily bright event or the L_x/L_{opt} ratio for stellar flares is a highly variable and as yet unpredictable parameter.

These calculations have been carried out in collaboration with the JILA group at Boulder. An initial account has been given by Haisch, Linsky, and Bowyer (1976), and a more thorough discussion has now been published in the Astrophysical Journal by Haisch, Linsky, Lampton, Paresce, Margon, and Stern (1977).

4. SIRIUS: MODELS AND INFERENCES

This binary system consists of a main sequence A star, Sirius A, and a DA white dwarf, Sirius B. The system is of considerable interest because Sirius B is the nearest and best studied of all white dwarfs, and thus offers the best constraints on models of the structure of these stars. The biggest observational uncertainty is the temperature (and hence the radius) of Sirius B. Conventional methods for making these determinations involve measuring the optical spectrum of the star. However, the presence of Sirius A only ten arc seconds away (and ten magnitudes brighter at visible wavelengths) causes large systematic errors in such data. Because the theory of stellar atmospheres shows that the EUV emission of a hot white dwarf must be extremely dependent upon its temperature, it follows that EUV data can in principle provide a very accurate thermometer for stars of this kind.

A second motive to obtain EUV data on Sirius is the possibility that white dwarfs may have coronas, just as the Sun has. Indeed, the ANS X-ray group has reported the detection of a weak, soft X-ray flux from Sirius, which they interpret as originating in a corona surrounding Sirius B.

Other soft X-ray measurements have not confirmed the ANS finding; if the flux is variable, it is almost certainly due to coronal or chromospheric activity. If the coronal hypothesis is correct, a substantial soft X-ray flux could be manifested without appreciable EUV emission.

Sirius was observed by the EUVT during orbit 80. Although a huge (54,000 cps) signal was seen in the barium fluoride UV band, no EUV flux was detected. The strong UV flux confirms that the telescope was correctly oriented towards Sirius.

These upper limits to the EUV emission immediately establish an upper limit to the photospheric temperature of Sirius B. The appropriate model atmosphere calculations by Dr. H. Shipman of University of Delaware were reported on by Lampton, Shipman, Margon, Bowyer, Paresce, and Stern (1976). The details of the analysis were recently published by Shipman, Margon, Bowyer, Lampton, Paresce, and Stern (1977), who showed that the EUV limits, the ANS soft X-ray observations, and the Copernicus UV data could be reconciled by postulating an effective temperature between 32,000 and 32,500 °K. Since the ASTP mission, further EUV measurements have been conducted by the Berkeley group and the data are presently being analyzed.

5. EUV CONSTRAINTS ON RADIO PULSARS

Radio pulsars are believed to be rapidly rotating neutron stars formed in supernova explosions over the last ten million years. The youngest pulsars should, in principle, show evidence of the high temperature at which they are formed; however, there has never been an unambiguous detection of thermal radiation from a radio pulsar. Such an observation would obviously be of great interest because it would provide a direct comparison of data with the theory of neutron star structure. It now seems fairly certain that the typical pulsar is not a strong thermal X-ray emitter; upper limits on X-ray emission from a variety of pulsars have typically constrained log T to less than 6.7. If the effective temperature of a typical pulsar is in the range $10^5 < T < 10^6$ °K, the bulk of the thermal radiation will appear in the EUV and for this reason included in the ASTP observing program were the three radio pulsars we mentioned, known to be nearby because of their small dispersion measures. In no case is there any evidence in the data for a signal in excess of background in any of the five ASTP channels for any of the three pulsars. These count rates can be used to derive upper limits to the incident flux at Earth from the pulsars, the most sensitive ones being for PSR 1929+10, of order of 10% of the flux observed from HZ 43. This corresponds to 6×10^{-26} ergs cm^{-2} sec^{-1} HZ^{-1} flux incident at Earth in the 170-620 Å band. Unfortunately the conversion of these observed limits into intrinsic luminosities and pulsar temperatures depends intimately on distance, interstellar hydrogen density n_H and radius R. Since none of these quantities are well known, the upper limits one can obtain must be parameterized by n_H and R. The maximum value of effective temperature permitted by the data in the most favorable cases (i.e., $n_H \sim 0.01$ cm^{-3}, R = 100 km) corresponds to $T_e \lesssim 1.6 \times 10^5$ °K, a far more stringent limit than can be set with X-ray data alone under those circumstances. In the worst cases ($n_H \sim 1$ cm^{-3}, R = 100 km) the limits are much weaker than those already set by the X-ray data. For two pulsars (PSR 1133+16) and 1929+10) the upper limits approach but do not violate the expected temperature from cooling or frictional heating theory. These conclusions have been derived from the EUV data by Greenstein, Charles, Margon, Bowyer, Lampton, Parsece, Stern, and Gordon (1976; 1977).

6. HZ 43 AND FEIGE 24

These two hot white dwarfs were the first EUV discoveries of the ASTP mission, and the initial reports and analyses were presented in the ASTP Preliminary Science Report. Since that time, additional research on these stars has been completed.

Concerning HZ 43, optical spectrophotometry has been obtained on both the white dwarf and red dwarf companion separately, leading to a spectroscopic classification and parallax. A trigonometric parallax has been obtained from 22 plates taken at the Allegheny Observatory, leading to an estimated distance of 65±15 parsecs. The effective temperatures and inferences as to the interstellar gas density presented in the discovery paper (Lampton, Margon, Paresce, Stern, and Bowyer, 1976) were confirmed. These results were presented in the Astrophysical Journal by Margon, Liebert, Gatewood, Lampton, Spinrad, and Bowyer (1976).

Other analyses of this important stellar system were recently published by Durisen, Savedoff, and Van Horn (1976) and by Auer and Shipman (1977). These groups considered the effects of composition on the opacity of the white dwarf's atmosphere and derived effective temperatures in the neighborhoods of 125,000 °K and 60,000 °K respectively.

Concerning Feige 24, extensive ground based observations by the Berkeley group have substantially augmented the meager information available at the time of the EUV discovery paper (Margon, Lampton, Bowyer, Stern, Paresce 1976). These new data, reported by Liebert and Margon (1977), provide a spectroscopic classification for the system and allow a distance of 90 parsecs to be derived. Meanwhile, the high resolution radial velocity study of Feige 24 (Thorstensen, Charles, Bowyer, and Margon 1976; Thorstensen, Charles, Margon, and Bowyer 1977) has revealed the system to be a spectroscopic binary with a 4.232 day period and a 67 kilometer/second amplitude. These data, in turn, allow the mass function of the system to be derived.

Summaries of these studies have been presented in the review papers by Lampton, Margon, and Bowyer (1976) and by Paresce (1976).

7. COMPUTER SEARCHES FOR NEW EUV SOURCES

The wealth of data returned by the EUVT has required the development of specialized computer software capable of analyzing the count rate information with the maximum possible sensitivity. This search has now been completed. No new sources were found during the target observation maneuvers. One new EUV source was discovered during the non-target scan maneuvers, and this discovery is described more fully here.

The scan maneuvers were usually performed at about .5°/sec so each 6 sec rotation of the filter wheel brought the 2.5° field of view to a new section of sky. In all, 820 separate fields in the sky were observed during scan maneuvers. The computer algorithm was employed to scan the data for statistically unlikely events. For each of the 820 points this algorithm calculated the total count rate and the number of standard deviations of this rate from a mean which was estimated by taking the average rate for 30 seconds on either side of the point in question. In the two filter bandpasses analyzed, four points of more than 3 sigma above the mean were found: one was coincident with a chance scan over the EUV source HZ 43, one with a chance crossing of the moon, and one was an unidentified point 3.0 sigma above the mean. Since the three sigma deviation above the mean has about a 60% chance of occurring in a sample of 820 points, we have discounted this point as noise and do not discuss it further.

The fourth point was 3.8 standard deviations above the mean and occurred in the 500-780 Å filter during a 0.5°/sec South to North scan in the southern constellation Pavo. The central bin has an excess of 160 counts which were distributed evenly through the eight 0.1 second telemetry bins, as is expected for a point source during this scan. We considered the possibility that this event was due to a charged particle event of some nature, but the signature of the event was quite different from any of the obvious charged particle events we observed which all had duration of only one or two telemetry bins. Furthermore, the helium glow experiment, which had similar filters and detectors and was coaligned with the EUV telescope, was also operational at the time of this observation and exhibited no increase in counting rate: hence a burst of electrons is clearly ruled out as the cause. The observation occurred at a quiet time of the orbit when the background, which was primarily solar 584 Å radiation backscattered by interplanetary HeI, remained nearly constant.

Statistical analyses show that there is only a small probability of so large a signal being a random fluctuation in the background data, and we are confident that the detection constitutes the discovery of another EUV star located in the constellation Pavo.

The intensity of the signal, when corrected for atmospheric absorption, becomes 265±70 counts per second in the 500-700 Å band, or [illegible] mJy. This flux is comparable to the intensities of HZ 43 and Feige 24 at 300 Å.

The Wisconsin X-ray group has surveyed this area of sky with a soft X-ray detector (Vanderhill et al. 1975) and has seen no evidence of a source. Their upper limit can be used to place constraints on simple spectral models for the EUV source. A simple bremsstrahlung model must have temperature less than 5.5×10^5 °K and a blackbody must have temperature below 2×10^5 °K. Simple power law models with no breaks are limited to those with spectral indices greater than 2.6.

What can be said as to the identification of the Pavo object? The source is expected to be nearby, as at 500 Å the interstellar absorption per H atom is about $1.2 \times 10^{-18} cm^2$ so that even with an interstellar hydrogen density of .01 cm^{-3}, three optical depths of absorption are expected within 100 parsecs. An unsuccessful search was made for nearby stars in the proper motion surveys of the area, indicating the source is probably not associated with a nearby main sequence star of type K or earlier. The nearby X-ray source 3U 1959-69 is also excluded on the basis of the most recent Uhuru position. An interesting possible candidate is the star HD 192273 which is unexpectedly bright at UV wavelengths. If this star is a subdwarf O star, a temperature between 30,000 and 50,000 °K might explain both the detection of flux at 500 Å and the lack of flux at 300 Å. These considerations are being published by Cash, Bowyer, Freeman, Lampton, and Paresce (1978).

8. THEORY OF EUV EMISSION FROM A HOT GAS

One application of EUV astrophysics is to the measurement of the temperature and composition of low density gases, such as are found in stellar coronae and in the interstellar medium. Emissivity calculations for a hot solar composition plasma have been completed by several authors. In the range 1-100 Å such calculations have been carried out by Landini and Fossi, Tucker and Koren, and Mewe; recently this range has been extended up to 250 Å by Kato. No such calculations have existed in the EUV (up to 1000 Å). Consequently, we have computed line emissivity functions for $\sim$ 700 lines in the range 100-1000 Å for conditions pertaining to a hot, optically thin, dilute plasma, which can be applied approximately to the cases of stellar coronae. This work is being published in the Astrophysical Journal Supplement by Stern, Wang, and Bowyer (1977) and a preliminary account was presented by Bowyer, Stern, and Wang (1976).

9. THE DIFFUSE EUV BACKGROUND

The soft X-ray background ($\lesssim$ 100 Å) has been studied in some detail recently by a number of experiments (e.g., the Wisconsin survey) and is having a major impact on our knowledge of the structure of the ISM. Basically this background has been shown to be highly variable over the sky with an intensity everywhere larger than an unabsorbed extrapolation of the high energy diffuse X-ray spectrum. The most likely origin of the observed emission is thermal radiation from a hot ($\sim 10^6$ °K) interstellar plasma because the required number and intensity of discrete soft X-ray sources appear to be insufficient to account for the observations. The available data on the soft X-ray background shows moreover that it cannot be explained by thermal emission from a hot gas at a single temperature under any reasonable assumption concerning the type of spatial emission model or the elemental abundances. The conclusions that can be derived from this type of work is that some emitting gas must be partly hotter than two million K and partly cooler than one half mission K. In other words, we must be seeing at least two different regions or phases of the ISM and perhaps our simple characterization of the ISM as consisting of two simple uniform hot and cold temperature phases is incorrect. Shapiro and Field have shown that the adoption of this picture runs into severe overpressure problems in a steady state formalism. Although the multi-temperature distribution might ease slightly this problem there is no a priori reason to believe the ISM must be in strict pressure equilibrium and in fact the available data might be taken as an indication of its dynamic behavior. This might not be surprising in view of the belief that the hot component is a result of interstellar tunnels created by interacting supernova remnants.

It is tantalizing to associate all or part of the observed soft X-ray emission to the hot OVI regions observed by Copernicus. The connection, however, is not so obvious since the gas observed at $\lambda < 100$ Å must be at temperature $T \approx 10^6$ °K and the OVI equilibrium distribution peaks at $T \approx 3\times10^5$ °K under normal ISM conditions both theoretically and experimentally. Thus the two techniques sample greatly differing regions of the ISM. The interconnecting link is afforded by observations of the diffuse EUV background $\gtrsim$ 100 Å and thus the EUV becomes a fundamentally powerful tool in our investigation of this multi-temperature and possible highly dynamic structure of the surrounding ISM.

Recently Stern, Bowyer, Paresce, Lampton, and Margon (1976) have completed the analysis of the EUV background measured in the parylene (90 Å) and beryllium parylene (120 Å) bands. These data spanned a total of 25 separate areas of the sky, covering a wide range of galactic latitudes. They confirm the steep rise in the spectrum with increasing wavelength already noticed before by our group and others, suggesting the emission is due to a different component than the high energy X-ray background.

Another major result is the remarkable spatial isotropy of the EUV background. The fundamental aspect of the available 120 Å background data is the fact that it is consistent at the 50% confidence level with a spatially uniform component, in stark contrast to the situation seen at shorter wavelengths. This result means that we are observing yet another hot component of the ISM distinct from the patchy one seen below 100 Å at temperatures $\sim 10^6$ °K, by our experiment and others. Isotropy seems to definitely increase with increasing wavelength.

Two enhanced regions were observed possibly associated with the extrapolated radio continuum loops of Haslam et al. and possibly indicative of emission from old nearby supernova supernova remnants such as those seen in X-rays. More work in these highly interesting regions must await future observations to confirm their existence and to delineate their spatial extent.

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