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Astronomy and the Extreme Ultraviolet Explorer Satellite

Stuart Bowyer

The extreme ultraviolet wave band (100 to 912 angstroms) was thought until recently to be useless to astronomy, primarily because the opacity of the interstellar medium would prevent observations at these wavelengths. However, the interstellar medium has been found to be markedly inhomogeneous in both density and ionization state and the sun is fortunately located in a region of low extreme ultraviolet opacity. The Extreme Ultraviolet Explorer, launched in June 1992, has surveyed the sky in this wave band and has detected a wide variety of astronomical sources at considerable distances, including some extragalactic objects. Studies in the extreme ultraviolet band have already begun to increase our understanding of the contents of the universe.

Introduction

During the early years of the National Aeronautics and Space Administration (NASA), numerous studies were published attesting to the promise of astronomy from space. These reports pointed to the potential rewards of astrophysical research in virtually every band of the electromagnetic spectrum—with one exception. In an influential paper, Aller (*1*) argued a point that was almost self-evident given the knowledge base at that time. The great absorptive efficiency of extreme ultraviolet (EUV) radiation of even very small amounts of neutral hydrogen gas, combined with the ubiquitous distribution of this gas throughout the interstellar medium (ISM), would mean that astronomy at these wavelengths is impossible. Indeed, in the initial reports of the discovery of celestial x-ray sources, the (presumed) opacity of the ISM was used as an argument that the first source discovered, Scorpio X-1, must be radiating at wavelengths shortward of 4 Å (*2*). Subsequently, considerable work was carried out to calculate the absorption of the ISM at x-ray wavelengths, but there was no inclination to extend these calculations to wavelengths longer than 100 Å, much less to question Aller's basic conclusions.

In the ensuing years, a substantial number of satellites were launched to carry out astronomical research over the entire electromagnetic spectrum. In particular, numerous satellites were deployed to study the wavelength bands that bracket the EUV regime. At wavelengths shorter than the EUV region, the x-ray band (covering wavelengths from 1 to 100 Å) has been extensively surveyed by UHURU, SAS-C, Ariel IV, Ariel V, HEAO-1, Einstein, EXOSAT, Ginga, ROSAT, Yohkoh, and others. At longer wavelengths, the far ultraviolet band (covering wavelengths from 912 to ~3000 Å) has been observed with ANS, Copernicus, IUE, and the Hubble Space Telescope. The wavelengths between ~100 and 912 Å nominally constitute the EUV regime (the once-named "unobservable ultraviolet"). This band received scant attention. Only within the past 3 years have the long-standing pessimistic predictions concerning the ability to carry out astronomy at these wavelengths been truly tested. The result of these new efforts has been a surprising wealth of data covering a wide range of astronomical phenomena.

The first all-sky search for EUV sources was carried out with the British Wide Field Camera flown as part of the German ROSAT satellite. This survey covered part of the EUV bandpass (60 to 200 Å) and yielded a catalog of 384 sources (*3*). The first all-sky, all-EUV band survey has now been completed with the NASA Extreme Ultraviolet Explorer Satellite (EUVE) (*4*). A first catalog of 410 sources has been provided (*5*), and the total number of EUV sources that we estimate we will ultimately find in the data set runs well into the thousands. NASA has offered the scientific community the opportunity to use the spectrometers on EUVE as guest observers; some 270 research teams (one-third of them from outside the United States) have applied to use these facilities.

Why were the original projections for EUV astronomy so far off the mark and why does this field now look to be so productive? Several factors, in combination, have provided the basis for this change. The ISM has been discovered to be far different, and hugely more EUV transparent, than originally believed. New technology has been developed providing much higher sensitivity than was expected both in broad-band survey work and in spectroscopic capabilities. Finally, the EUV band has provided scientific bonuses not originally envisaged.

A variety of evidence garnered in the 1970s showed that the ISM was clearly not homogenous and that there was a marked deficiency of neutral interstellar gas in the sun's vicinity. The discovery of the diffuse soft x-ray background and interstellar O VI absorption indicated the presence of hot, ionized gas that would not contribute to the EUV opacity. The characterization of the ISM is far from clear [see (*6*) for a recent review], but all this work strongly suggests that the EUV opacity of the ISM within 1000 light years is far less than originally prophesized.

Dramatic proof of the viability of EUV astronomy was provided by a University of California at Berkeley EUV telescope flown as part of the Apollo-Soyuz mission in 1975. Bright EUV emission was detected from the hot, white dwarf star HZ 43 located at a distance of ~180 light years in the constellation of Coma Berenices (*7*). Three more sources were also discovered during this mission: the hot white dwarf Feige 24, the cataclysmic variable star system SS Cygni, and a late-type star, Proxima Centauri.

A major obstacle to the development of EUV astronomy was the lack of suitable technology. At visible, infrared, and ultraviolet wavelengths observations are usually made with telescopes whose mirrors collect the incoming photons in a "normal incidence" mode (that is, the light rays hit the mirror perpendicularly); the rays are subsequently brought to a focus and detected with film or an electronic detector. However, at wavelengths shorter than about 500 Å, normal incidence telescopes cannot be used because the photons are totally ab-

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sorbed by the mirror. However, if EUV photons strike a very smooth mirror at a small angle (that is, in a "grazing incidence" mode), the reflectivity of the mirror becomes quite high and the photons can be gathered and brought to a focus. This concept was developed for the field of x-ray astronomy, but the glass mirrors used in that work cost many millions of dollars each. Grazing incidence metal mirrors, costing more than an order of magnitude less than glass mirrors, were developed at Berkeley for EUV astronomy as part of my NASA sounding rocket program. The performance of these metal mirrors approaches that of the glass mirrors used in x-ray astronomy (*8*).

Starting with the earliest work in EUV astronomy (*7*, *9–12*), the lack of suitable detectors was a major obstacle. In the ensuing years, a number of detectors suitable for EUV space astronomy were developed in my laboratory. All of these detectors use multi-channel plates (the primary element in night-vision goggles) with innovative spatial readout systems. The detectors in EUVE use "wedge and strip" encoding invented by Lampton and co-workers (*13*) and developed and space-qualified by Siegmund and co-workers (*14*). These detectors provide 1680 by 1680 independent resolution elements, are linear to better than 0.5%, and possess a variety of additional attributes: They are stable, rugged, and solar-blind, and display graceful degradation with higher counting rates.

Spectrometers suitable for use at EUV wavelengths were also a major problem. The design of choice for solar EUV studies was a grazing incidence version of the classic normal incidence Rowland spectrometer. This adaptation of a normal incidence design to a grazing incidence configuration had many deficiencies. The spectrometers in EUVE are an entirely new design first proposed by Hettrick and Bowyer (*15*) and developed in my laboratory. This class of spectrometer uses gratings with variable line spacing and provides substantial advantages for use with grazing incidence optics. First, it is highly efficient in that it requires a minimum number of reflections. Second, the image plane is normal to the direction of the principal ray, eliminating distortions inherent in the grazing incidence Rowland design. Finally, it is inherently flexible in combination with grazing incidence optics, providing the opportunity to optimize features such as compactness, plate scale, and resolution.

The Extreme Ultraviolet Explorer

The science instruments aboard EUVE were designed, built, and tested at the Space Sciences Laboratory at the University of California, Berkeley. They consist of three 40-cm aperture grazing-incidence scanning telescopes, three EUV spectrometers, and a deep survey–spectrometer telescope (*4*). On 7 June 1992, EUVE was launched into Earth's orbit. After a 1-month, on-orbit check-out phase, EUVE began a 6-month all-sky survey in its four EUV photometric band passes (60 to 180 Å, 160 to 240 Å, 345 to 605 Å, and 500 to 740 Å), simultaneously searching the entire EUV spectral band for celestial sources. Concurrent with this sky survey was the operation of a short-wavelength (65 to 190 Å and 160 to 360 Å) deep survey of a 2°-wide swath along half of the ecliptic at a sensitivity some 10 to 50 times that of the all-sky survey. On completion of the EUVE sky survey in mid-1993, guest observers chosen by NASA began using the three spectrometer channels that covered the 70- to 760-Å region at a resolving power of ~250. Over 80 science investigations were scheduled during the first 12 months of the guest observer spectroscopy program. At the time of this writing, all the instruments on EUVE continue to exceed or meet their operational requirements, and the mission has now passed the 18-month mark with no major interruptions or instrument failures.

The first EUVE source catalog lists the 410 brightest sources detected in the four-band sky survey (*5*). Probable optical identifications have been made for most of these sources; the types of objects detected are shown in Table 1. In the remainder of this article, I will outline some of the preliminary results from the all-sky survey and a few selected highlights from the first EUVE spectroscopic observations.

Table 1. Phenomena observed. Abbreviations: *n*, number of objects; QSOs, quasi-stellar objects.

Object	*n*
Late-type stars (F, G, K, M)	183
White dwarfs	106
Early-type stars (O, B, A)	32
Cataclysmic variables	14
Planetary nebulas	3
X-ray binaries	1
Novas	1
Active galactic nuclei	3
QSOs and BL Lacs	6
Supernova remnants	2
Solar system objects	2
No identification	61

Surprises

A major surprise in the sky-survey data was the detection of a distant hot B2II star, ε Canis Majoris (CMa) (*16*). This star, more than 600 light years distant, was strongly detected in the two long-wavelength EUVE band passes. The flux in the longest wavelength band (500 to 740 Å) is some 30 times brighter than that of the EUV source previously believed to be the brightest, the hot white dwarf HZ 43. The EUV emission was so intense that it triggered an automatic detector rate shutdown, conservatively set before launch to protect the detectors from unexpected high count-rate events. This minor problem was quickly solved, and observations of ε CMa continued.

EUVE spectroscopic observations of ε CMa by Cassinelli and colleagues (*17*) have shown it to be extremely rich in stellar photospheric emission lines longward of ~450 Å and to possess short-wavelength flux at ~170 Å, probably because of emission from shock-heated plasma in its stellar wind. Preliminary fits to the photospheric spectrum with standard ("well understood") B star model atmospheres have failed to reproduce both the numbers and type of observed spectral features and dramatically underestimate (by a factor of 30) the level of emission at ~500 Å. This result will not only require major revisions in our understanding of the atmosphere of hot stars but will also change our understanding of the sources of photoionization of the ISM.

Estimates of the EUV source horizon have grown increasingly larger with new knowledge of the ISM, but the detection of extragalactic EUV sources seemed unlikely. A detailed analysis of the relevant radio data on neutral hydrogen in our galaxy led Heiles (*18*) to conclude that no extragalactic objects could be detected in the EUV. Hence, a surprising result from the all-sky survey was the detection of nine extragalactic objects: three active galactic nuclei (AGN) galaxies, four BL Lacertae (BL Lac) objects, and two quasi-stellar objects (QSOs). Preliminary spectroscopic data on one of the BL Lac objects, PKS 2155-304 (*19*), show continuum emission to ~110 Å with a suggestion of absorption features. More extensive spectrographic observations of this object are scheduled, but the limited data now available are sufficient to provide the first estimate of neutral helium in the ISM through the entire halo of the galaxy. We find that neutral helium constitutes 9 to 10% of the neutral hydrogen in this direction.

Late-Type Stars

Stars like our sun that possess chromospheres and coronas ("late" stars or "cool" stars) form the largest subset of sources detected in the EUVE all-sky survey, and EUV spectroscopy of these objects will have a large impact on our understanding of the physics of stellar coronas. Analysis of the count rates in the four EUVE photometric band passes can be used to constrain the temperatures of coronal emission from such sources. Vedder and co-workers (*20*) have reported results for two

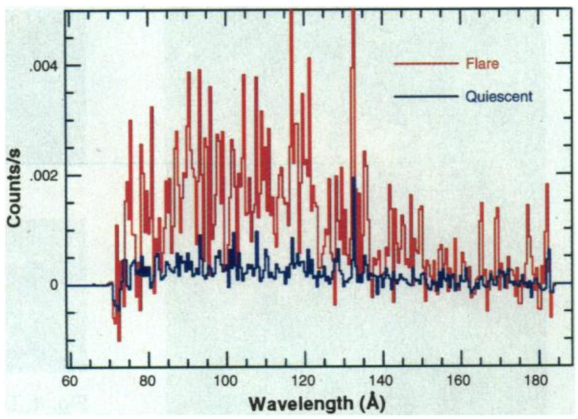

Fig. 1. The short-wavelength (70 to 190 Å) EUVE spectrum of AU Mic in both quiescent (lower) and flaring (upper) states (from the EUVE public archive).

late-type stars, α Centauri (Cen) (G2V + K1V) and HR 6094 (G5V). Two distinct temperature components are required for the α Cen binary system: one with a temperature of 8.5×10^5 K and a second with a temperature of 1.0×10^5 K. These results indicate that, at least for these two stars, a different temperature distribution than previously thought for late-type stellar coronas is required to explain the observed EUV emission.

Dupree and colleagues (*21*) have carried out EUV spectroscopic observations of the G0III binary system of Capella. The data show a rich emission spectrum from 70 to 400 Å; this spectrum is dominated by high-ionization emission lines of iron (Fe XV to Fe XXIV). Contrary to earlier x-ray results that were interpreted as emission from components at two separate temperatures, the EUV results show that a continuous distribution of temperatures from 10^5 K to 6×10^7 K are present in the Capella system. A surprising result is that there appears to be a minimum in the emission-measure distribution at ~1 million K. This feature differs from that of the solar atmosphere, whose minimum occurs at ~160,000 K, the temperature at which the maximum radiative loss rate for a collisionally ionized plasma occurs. Hence, the EUVE data show an atmospheric temperature structure for Capella that is different from that of the sun. The reasons for this fundamental difference are not clear.

Numerous late-type stars, particularly the dM stars, are known to flare from time to time at visible and x-ray wavelengths. During the in-orbit calibration phase of the EUVE deep-survey telescope, a flare was observed on the star AU Microscopii at a count rate some 20 times greater than that at quiescence (*22*). The flare event consisted of a sharp peak in the level of EUV emission that lasted for 2 hours, followed by a decaying tail that lasted more than a day. The total energy of this event has been estimated to be 3×10^{34} ergs, with an emission measure of $\sim 6 \times 10^{53}$ cm^{-3}. This value indicates that large volumes of material are involved in these flaring processes, with flare-loop lengths estimated to be the size of at least one stellar radius. EUV spectra of the quiescent and flare emission of AU Mic are shown in Fig. 1. These spectra are now under analysis by several groups; it now seems possible that the level of activity is so pronounced that time-resolved spectrophotometry can be carried out with these data.

Hot White Dwarfs

Observation of hot white dwarf stars in the EUV is of great interest for several reasons. First, substantially new phenomena have been discovered, and new pathways for the evolutionary path from planetary nebula to cool white dwarfs have been suggested. Second, the EUV continuum of these objects can be used as a source of background emission against which the absorption effects of the intervening ISM can be measured.

The EUVE spectrum of the hot white dwarf GD 246 (Fig. 2) exhibits features from a stellar atmosphere that radically depart from that of the pure hydrogen atmosphere suggested by the visible spectrum. A spectroscopic survey of very hot [effective temperature (T_{eff}) >45,000 K] and relatively bright hydrogen-rich (DA) white dwarfs initiated more than a decade ago with the International Ultraviolet Explorer revealed the presence of a few heavy elements (C, N, O, Si, and Fe) in the photosphere of a few of these objects. A more complex picture is emerging from EUV observations. A host of heavy elements was detected in the EUV spectra of the DA white dwarfs G191 B2B and GD 246 (*23, 24*). These heavy elements strongly influence the thermodynamic properties of the atmosphere of the stars because of their large EUV radiative opacity. New model atmospheres that include radiative cross sections for heavy metals, combined with chemical separation (diffusion) in the presence of strong gravitational and radiation fields, appear to be the key in explaining the abundance patterns being found.

The standard evolutionary scenario for white dwarfs is that they evolve from the post–asymptotic giant branch (AGB) regime of the Hertzsprung-Russell diagram with the expulsion of a planetary nebula. However, problems do exist with this scenario. An observational test can be made by comparison of the space densities and birthrates of planetary nebulas with the space densities of hot white dwarf stars. Until EUVE, the best estimate for this parameter was derived from the Palomar-Green optical survey that indicated a space density of less than three hot white dwarfs per 36×10^6 cubic light years (*25*). This small number was in substantial conflict with the standard scenario. The hot white dwarf density found with EUVE is at least five times larger than the Palomar-Green–derived number and is in agreement with the idea that most, if not all, white dwarfs emerge from post-AGB evolution (*26*).

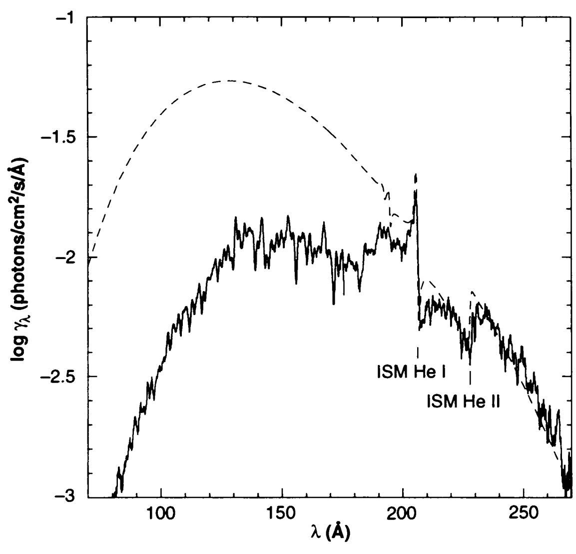

Fig. 2. The EUVE spectrum of the hot white dwarf GD 246 (WD2309 + 105), showing absorption edges due to interstellar He I and He II gas. Also shown is a pure hydrogen, stellar atmosphere model (T_{eff} = 55,000 K), as suggested by the optical data on this object. Note the radical departure from the observed spectrum for wavelengths <200 Å [from (*24*)].

Planetary Studies

EUVE observations of three solar system objects, the moon, Mars, and the Jupiter-Io system, have been carried out. The moon was observed on several occasions during the all-sky survey phase of the mission, and Gladstone and colleagues (*27*) have reported lunar surface albedo measurements over the entire 70 to 760 Å range that have been modeled with the use of the scaled bulk reflectivities of SiO_2 and Al_2O_3 materials. An EUV image of the moon at the first quarter stage is shown in Fig. 3. The total counts in such images are being used by Gladstone (*28*) to monitor the variation of solar EUV flux. These data are important for us on Earth, because small changes in the incident EUV solar flux on the Earth's upper atmosphere have a large effect on the photochemical absorption rates in the thermosphere for atomic species such as O, N, and H.

EUV spectral observations of the Martian atmosphere by Krasnopolsky and colleagues (*29*) have provided the first measurement of helium gas on Mars. This result was obtained by the measurement of He II, 584 Å resonantly scattered solar radiation. Helium in the Martian atmosphere is introduced through outgassing from the radioactive decay of Th, Ur, and K in the Martian interior. This input is in equilibrium with losses to space, and atmospheric helium has an exchange lifetime of ~50,000 years. The EUVE measurements have been used to derive the He mixing ratio, which can be combined with other existing Martian data to provide a key parameter: the radiogenic heat flux of the planet. This parameter is found to be a factor of 7 less than that measured for the planet Venus. The radioactive elements in Mars reflect the amount of this material in the protoplanetary cloud from which Mars was formed. This value can be compared with similar data for Earth and Venus. These data indicate that there were substantial abundance variations of K, U, and Th in the solar system protoplanetary cloud.

The Jupiter-Io system has been known as a source of EUV emission since Voyager spacecraft observations in the late 1970s provided broad-band (~30 Å) EUV spectra of the system. In Fig. 4, we present the first spectral images of the "doughnut"-shaped ring (torus) of super-hot ionized gas surrounding Jupiter, as recorded by the EUVE spectrometers (*30*). The figure shows two striking images of the Io plasma torus, with the orbit of the giant planet and its satellite Io inset. The top image shows light emitted at a wavelength of 680 Å by doubly ionized sulfur ions, and the bottom image shows light emitted at 593 Å by neutral oxygen atoms. The brightest areas are depicted in red and correspond to the most intense EUV emission. The doughnut-shaped torus is located roughly on the path of Io's orbit around Jupiter.

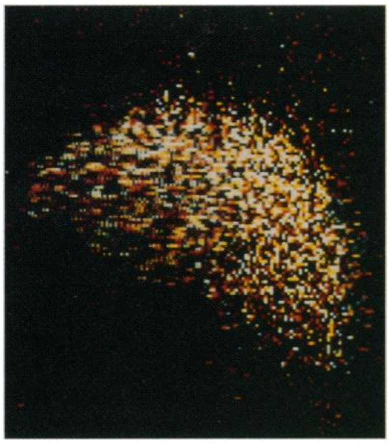

Fig. 3. The moon as seen at EUV wavelengths. The radiation is solar flux reflected by the lunar surface.

It is clear from data in the figure that the EUV emission is far brighter on one side of Io's orbit than it is on the other, indicating that the gas there is in a much hotter environment. Because the EUV emission mechanism for the Io plasma torus is powered in part by Jupiter's strong rotating magnetic field, the EUVE data indicate the presence of a large asymmetry in the distribution of the Jovian field lines that interact with the volcanically liberated sulfur and oxygen atoms from the Io satellite atmosphere.

Local ISM Studies

A result of considerable interest obtained from a portion of the Deep Survey data has been the discovery of a shadow in the diffuse EUV background. This shadow was found to coincide with an isolated IRAS cirrus cloud. Shadows in the diffuse emission from the hot ISM have been observed in the x-ray band, but attempts to derive some of the key physical parameters from these observations have been foiled by the penetrating power of x-rays. In particular, the emission measure of the plasma cannot be directly measured; instead, detailed modeling is required, with assumptions as to the opacities of unknown intervening cooler cloud material (*31*). In contrast, the shadow detected with EUVE is at lower energy, and the cloud involved forms an opaque shield to more distant emission. This shield isolates emission from the plasma between us and the cloud and permits a precise determination of the character of the emitting plasma. An analysis of this data provides the first direct measurement of the thermal pressure of the hot ISM. This pressure is surprisingly high: It falls in the range of P/k = 9,000 to 14,000 K/cm^3 (where k is Boltzman's constant) depending on the exact distance to the cloud (*32*).

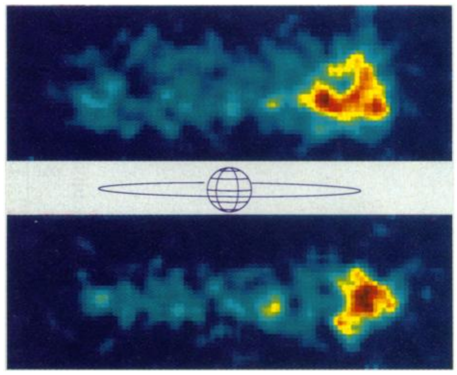

Fig. 4. Two images of the Io plasma torus. The top image shows 680 Å light emitted by S II ions, and the lower image is for O I atoms at a wavelength of 539 Å. The brightest areas are shown as red and the faintest as blue [from (*30*)].

The ionization state of the local ISM has been the subject of over a dozen investigations; the results reported are essentially a scatter diagram. EUV observations of the absorptive effects on the continuum of hot white dwarfs with rocket-borne instruments (*33*) and with the Hopkins Ultraviolet Telescope (*34*) provided the first direct measurements relevant to this problem, but these measurements only provided a determination of the neutral helium to neutral hydrogen ratio in the ISM. The comprehensive wavelength coverage of the EUVE spectrographs offers the capability of direct, model-independent measurements of both neutral and ionized helium in the ISM. Vennes and co-workers (*24*) report observations of the hot white dwarf GD 246 obtained with EUVE. This spectrum provided the first observational evidence for ionized helium in the ISM; at $\lambda > 200$ Å, the spectrum reflected a classic white dwarf hydrogen atmosphere, but with a superposed strong absorption feature from ionized ISM helium. They estimated the helium ionization fraction He II/(He I + He II) $\approx$ 25%, with a total helium column of 1.40×10^{18} to 1.65×10^{18} cm^{-2}. They also obtained the neutral hydrogen column density from the EUV continuum absorption to be a column of 1.2×10^{19} to 1.6×10^{19} H I cm^{-2}. Similar studies using white dwarf stars in different view directions will provide a detailed map of the ionization state of the local ISM.

Conclusions

The initial results from EUVE have demonstrated that important new information on a wide variety of astronomical objects will be provided by studies at EUV wavelengths. Although most EUV observations will concentrate on galactic objects, it is truly remarkable that at least some extragalactic objects will be accessible for detailed study. The age of EUV astronomy has arrived. Our understanding of the contents of the universe will be enriched as a consequence.

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