A Comprehensive Review of....
All You Really Need to Know About...
What I Feel Like Telling You About Fifty Forty Years of Extreme and Far Ultraviolet Astronomy at the Space Sciences Laboratory

-Mark Hurwitz, with helpful input from Stu Bowyer, Ossy Siegmund, Chris Martin, Simon Labov, Jerry Edelstein, and Damian Christian no one else to blame

• Some Technology Items
• Brief Chronology of SSL’s EUV Missions, with Commentary not to be Construed as Whining
• Cool Science Topics, Some Not Yet Published

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Why Do Astronomy in the EUV / FUV Spectral Range?

Wavelengths between 10 – 200 nm contain:

• Resonance absorption lines of abundant elements in interesting ionization stages, from H I through O VI, sampling gas temperatures from ~10 to ~10^5 K

• Ionization edges of H, He I, He II, and other species

• Resonance absorption lines of the most abundant molecule, H₂

• Peak thermal emission for blackbody spectra between about 10^4 to 10^5 K
EUV Detectors, Circa 1970

HIGH SECONDARY EMISSIVE SEMICONDUCTIVE SURFACE
CASCADING ELECTRONS

Ground
Ion Path
Electron Cascade
Signal Out
~ +2 keV

INCOMING RADIATION
PREAMP
CHARGE COLLECTOR
HV

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Two-Dimensional Detector Systems Developed at SSL

Lampton / Siegmund / Vallerga / Jelinsky / Tremsin / Martin / Edelstein / Hurwitz / Sirk / Hull / Hemphill / Others

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Experimental Astrophysics Group
UC Berkeley ---- Mission Experience
Dr. Oswald Siegmund
Grooves uniformly spaced, mechanically ruled or recorded in photoresist interferometrically (low efficiency)
Grooves variably spaced, mechanically ruled on: Planar (EUVE), spherical (ORFEUS), or cylindrical substrate (CHIPS)

Malina / Cash / Hettrick / Jelinsky / Hurwitz / Edelstein / Hemphill / Sirk / Others
Other UV Technologies Developed or Advanced at SSL

**Telescopes** (Henry / Cash / Malina / Hettrick / Lampton / Finley / Jelinsky / Labov / Bixler / Sasseen / Sholl / Korpela / others)

**Filters** (Chakrabarti / Hemphill / Vallerga / Jelinsky / Labov / Hurwitz / others)

**UV Light Sources** (Paresce / Finley / Others)
Other Technologies Developed or Advanced at SSL, Continued

Novel Interferometers (*Edelstein / Korpela*)

And OF COURSE a great deal of the work in many of these areas has been supervised and inspired by Prof. C. Stuart Bowyer
History of EUV Missions at SSL, or How to Develop a New Field of Space Astronomy

Develop instruments to investigate this proposed new field
Then get someone to put your instruments into space

1966 - 1970 Developmental EUV instruments secretly flown on Berkeley's X-ray rocket flights

1972 Berkeley EUV single band all-sky survey selected for NASA's next OSO Mission

1973 Next OSO Mission canceled

1975 Berkeley instrument selected for Apollo-Soyuz Mission; detects 4 EUV sources

1976 Berkeley's single band EUV all-sky survey selected by Department of Defense for flight in 1980

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History of EUV Missions at SSL, or How to Develop a New Field of Space Astronomy

1976 Berkeley Extreme Ultraviolet Astronomy Explorer (EUVE) 4-band all-sky survey selected by NASA for flight in early 80's

1979 National Academy of Sciences Panel (dominated by X-Ray astronomers) recommends NASA cancel EUVE since "There are probably no more than a dozen or so EUV sources and discovering these is not a good use of resources". Recommends they put the money into X-ray astronomy.

1981 A high level NASA official asks Berkeley to propose our secret spectroscopy option for EUVE, later states "I thought I would get the X-ray crowd arguing about spectroscopy and stop trying to kill the survey mission."

1982 Berkeley proposes a unique variable line space grating spectrometer for EUVE. NAS opposition collapses. Survey mission with spectroscopy endorsed.
History of EUV Missions at SSL, or How to Develop a New Field of Space Astronomy

1984 Germany's Space Agency agrees to a joint German/Berkeley EUV/FUV stellar spectroscopy project (NASA gets into the act at a later date)

1985 DOD cancels EUV single band all-sky survey mission

1987 Spanish Department of Defense agrees to fly a Berkeley EUV spectroscopy instrument (EURD) on their first satellite

1990 University of California establishes the Center for Extreme Ultraviolet Astrophysics

1992 EUVE launched

1993 Berkeley’s EUV stellar spectrometer flown on the German ORFEUS-SPAS platform
1994 NASA chooses a Berkeley EUV spectroscopy instrument (UCB) to fly on their "Fast Track Satellite" mission. (A big plus was that this instrument was already well developed and hence was low cost and low risk; it was, in fact, the EURD instrument. A second instrument was started for the Spanish mission)

1996 Berkeley's EUV stellar spectrometer flown on the third flight of the German ASTRO-SPAS platform

1997 Berkeley's UCB instrument launched; satellite fails to reach orbit

1997 EURD launched and begins 2 years of successful ops

2003-2008 Launch and successful operation of NASA’s first (and only) University-Class Explorer, “CHIPS”
EUVE Mission

- Launched June 1992
- 6 month all-sky survey
- 8+ years pointed spectroscopy
- Also serendipitous photometric obs with survey telescopes == Right Angle Program (RAP)
EUVE Mission

Results include:
Newly-discovered flare stars

White dwarfs, including a rotating one with a cool spot!
EUVE Mission

Spectroscopy and light curves to constrain the geometry of cataclysmic variables...

And too much more to describe here.
The **Very** Local Interstellar Medium
Sun-centered contour of neutral interstellar material is based on absorption lines of Na I toward nearby stars and corresponds to optical depth unity at about 200 Å. Triangles indicate position of Galactic and extragalactic point sources detected with EUVE.
Soft X-ray sky map of Snowden et al. Most of the diffuse local emission is believed to arise in a hot \((10^6 \text{ K})\) plasma within the nearest \(\sim 100\) pc. Discrete features include supernova remnants, “radio Loop I,” etc. The diffuse background brightens generally near, but not precisely at, the Galactic poles.
Diffuse Extreme Ultraviolet Radiation

- Presence of diffuse X-ray emission and absence of nearby neutral interstellar gas led to the “local hot bubble” model of the interstellar medium. Copious EUV emission expected. But not detected by Labov sounding rocket…
Diffuse Extreme Ultraviolet Radiation

• Nor by EUVE or CHIPS...
• So the local interstellar cavity must be filled w/ gas that is either cooler, hotter, or depleted in iron than the models developed from X-ray observations.

• But for some reason, this field of study inspires contributions from particularly colorful amateurs. Will share those if time permits at end of talk / during question period.
By 1980, it was known that the integrated far ultraviolet glow at high galactic latitudes was brighter than could be accounted for by adding up the light from faint stars in our Galaxy…
Origin of the Far Ultraviolet Background / Molecules at High Latitude

But did the glow arise primarily outside the Galaxy, in which case it should be faintest where there is significant Galactic dust along the sight line…

or did it come primarily from the dust itself, reflecting the UV starlight from our Galaxy, in which case it should be brightest where the dust is?
Origin of the Far Ultraviolet Background / Molecules at High Latitude
Origin of the Far Ultraviolet Background / Molecules at High Latitude
Results of study of high-latitude FUV background and absorption line studies:

• There is molecular gas (H$_2$) along virtually all sight lines. Comes as a surprise to many astronomers, but not those who remember *Copernicus* results (1970's).

• UV starlight scattered from dust produces most of the diffuse background

• H$_2$ fluorescence significant along some sight lines

• Highly ionized gas produces emission lines (esp. C IV)

• Two-photon recombination continuum from “warm” photoionized gas

• Extragalactic background about ~10% of the total in the faintest regions

• GALEX studies SFR in relatively low-redshift universe

• Measure dust grain albedo and scattering phase factor (see my TMC paper)
SPACE SCIENCE LABORATORY

CHIPS: From Selection to Science Magazine in Only 6 Months!

Last summer, astronomer Mark Hurwitz won a coveted NASA grant to build one of the first members of a new generation of small, bargain-priced science satellites. But there was a catch: The University of California, Berkeley, researcher had to find a way to launch his payload, called the Cosmic Hot Intergalactic Plasma Spectrometer (CHIPS). So Hurwitz designed his 25-kilogram instrument as a mechanical parasite that would hitch onto a U.S.-built communications satellite to be launched by a Russian rocket in 2001 or 2002.

End of story? Hardly. Instead of being a solution, that arrangement was only the beginning of Hurwitz’s problems.
Counts ($10^4$)

- 171.073 Fe IX
- 174.531 Fe X
- 182.169 Fe XII
- 184.597 Fe X
- 186.887 Fe XII
- 186.232 Fe XI
- 190.037 Fe X
- 192.344 Fe XII + O V
- 193.506 Fe XI
- 193.119 Fe XIII
- 201.128 Fe XIII
- 202.044 Fe XIII
- 203.626 Fe XIII
- 209.321 Fe XIII
- 211.318 Fe XIV
- 215.2 O V
- 216.9 Si VIII + Fe XIII
- 219.131 Fe XIV
- 220.961 Fe XIV
- 221.827 Fe XIII
- 225.625 Si IX
- 227.062 Si IX + Fe XIV
- 233.562 C IV + Fe XV
- 235.505 Fe XIII
- 237.339 He II
- 238.380 O VI
- 239.600 Fe XIII
- 240.890 Fe IX
- 243.830 He II
- 244.596 Fe IX
- 246.211 Fe XIII
- 251.256 Fe XIII
- 255.371 Si X
- 258.299 He II
- 259.644 Si X
- 263.790 Fe XIV
- 256.3 He II
- 270.522 Fe XIV
- 272.640 Si VII

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Figure 4. Integrated Al filter lightcurve (upper panel), and Hot to Cool ratio (dots) compared to SOURCE XPSL4 flux (gray line, lower panel). The diamonds in the lower panel denote the two extreme times chosen for the SOHO EIT images depicted in Figure 7.
Both CHIPS “hot state” and “cool state” solar spectra can be well-modeled in CHIANTI…
EUV Solar Spectroscopy with CHIPS

But there are significant differences between our CHIPS spectrum and the SORCE XPS Level 4 CHIANTI model. If modeling the effect of solar EUV on planetary atmospheres, use the right spectrum!

Figure 9. CHIPS spectrum binned at 0.11 Å (black line) scaled to XPSL4 binned at 1.0 Å (gray histogram). The inset plots the nominal effective area curves of CHIPS multiplied by the modeled efficiency curve of the light leak.
Conclusion: Astronomers at SSL have done and continue to do a lot of interesting work in the far and extreme ultraviolet – thanks for the opportunity to share a small part of it with you.
H$_2$ at High Galactic Latitude Shouldn’t Have Come As a Surprise

- Traditional radio surveys of molecular gas map $^{12}$CO or $^{13}$CO, sampling dense regions only.
- Fosters a mindset that there is no molecular gas at high latitudes
- Many astronomers forgot the results from Copernicus (1970’s)
- Even small amounts of H$_2$ absorb much of the FUV spectrum
• Cool / warm IGM contains much of the baryonic mass of the universe. At high redshift, ~100% of the expected baryons are accounted for.

• Ly β lines toward nearby 3C 273 seen with ORFEUS indicate higher columns of cool / warm gas than estimated from Ly α. Helps reconcile the “missing baryon” problem – about 50% are missing at low redshift. Remainder presumably in hot IGM.
From Launch to National Geographic in 14 Months!

A new space probe called the Cosmic Hot Interstellar Plasma Spectrometer, or CHIPS, is looking for signs of those embers in what scientists call the local hot bubble, but so far has only found traces of them. The local hot bubble doesn’t seem to be that hot, and the emptiness can’t yet be explained. But CHIPS will keep looking.

The way things are arranged gives us clues to our galactic past. “It’s like archaeology,” says Mark Hurwitz, principal CHIPS investigator. “The galaxy is not in perfect equilibrium. It’s constantly percolating, stirred up by supernovae.”
Emission spectrum of $10^6$ K gas attenuated by “local cloud” of $2 \times 10^{18}$ cm$^{-2}$. Solar abundance and collisional ionization equilibrium are assumed. Brightest lines: Fe X 174.6Å, Fe IX 171.1Å, Fe XI 180.4Å, Fe XII 186.9Å