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A Spatial Heterodyne Spectrometer for Laboratory Astrophysics; First Interferogram

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ABSTRACT

A Spatial Heterodyne Spectrometer with broad spectral coverage across the VUV - UV region and with a high ($>$ 500,000) spectral resolving power is being built for laboratory measurements of spectroscopic data including emission branching fractions, improved level energies, and hyperfine/isotopic parameters.

1. Introduction

Fourier Transform Spectrometers (FTS's) are important to Laboratory Astrophysics programs including the Univ. of Wisconsin effort on atomic transition probabilities. Instruments such as the McMath 1 m FTS at the National Solar Observatory on Kitt Peak have many advantages. They provide a very high spectral resolving power, broad UV to IR wavelength coverage, exceptional wavenumber accuracy and precision, a large etendue, and a high data collection rate. There is an additional advantage of a FTS for measurements of emission branching fractions over large spectra ranges; an interferogram is a simultaneous measurement of all spectral resolution elements. This last advantage makes a FTS insensitive to source intensity drifts during branching fraction measurements. Although the McMath 1 m FTS has been extraordinarily successful in the UV-visible-IR regions for approximately 3 decades, there is critical need for an equally productive instrument in the VUV.

The need for basic spectroscopic data in the VUV arises in part from local Universe observations, such as studies of the Interstellar Medium (ISM) and chemically peculiar stars of our Galaxy, and from high redshift studies of the ISM of distant, young Galaxies. Quantitative spectroscopy yields most of the detailed physics and chemistry of such studies. The opportunities for high redshift observations will be dramatically improved with the launch of the James Webb Space Telescope.

We are building a new type of FTS called a Spatial Heterodyne Spectrometer (SHS) to meet the needs of Laboratory Astrophysics in the VUV (Harlander and Roesler 1990). The availability of large format, 2 dimensional detector arrays makes it possible to build high performance SHS's. In a traditional FTS based on a Michelson interferometer, at least one mirror is moved to record an interferogram as a function of mirror position (or time) using a single channel detector. In a SHS the interferogram is spread out in space and is projected onto a detector array. The lack of moving parts in SHS instruments simplifies their design and construction and makes these instruments compatible with transient, low duty cycle sources. Furthermore, a SHS is somewhat more tolerant of optical imperfection than a traditional FTS based on a Michelson interferometer. These advantages, and the prospects of building an all reflection SHS for VUV operation, have inspired us to design and build a broadband, very high resolution SHS for the VUV. This paper is a progress report on our project.

2. The Mark 1 SHS

Figure 1 is a schematic of our Mark 1 SHS which is built around a CaF_2 beamsplitter and a matched pair of very coarse (23.2 groove/mm) echelle diffraction gratings. Our Mark 1 SHS will have VUV capability, but it is limited to wavelengths above the CaF_2 transmission cutoff. Order separation, scattered light, and phase stability issues in broadband, high resolution SHS instruments are being addressed using our Mark 1 SHS. Lenses are shown in Figure 1 as the collimating and imaging optics only to simplify the figure. Off-axis mirrors are actually being used.

Essential features of the Mark 1 SHS are easy to understand since its geometry is similar to a Michelson interferometer. The flat phase fronts in Fig. 1 coming from both gratings at the exact Littrow condition recombine at the beamsplitter to form a broad light or dark fringe. This fringe is a Fizeau fringe localized near the projected crossing point of one grating with the virtual image of the other. Phase fronts for a wavelength above or below the Littrow wavelength are tipped, and these cross each other to form Fizeau fringes running perpendicular to the plane of the figure. The fringe frequency is proportional to wavelength separation from Littrow. The ambiguity of equal fringe frequencies above and below Littrow, and the ambiguity of different grating orders, can both be resolved by tipping one of the gratings about an axis in the plane of the figure and parallel to the Littrow phase fronts. Detailed equations for the SHS fringe frequency and desired cross tip angle have been published (Harlander and Roesler 1990). We will focus in subsequent paragraphs on design

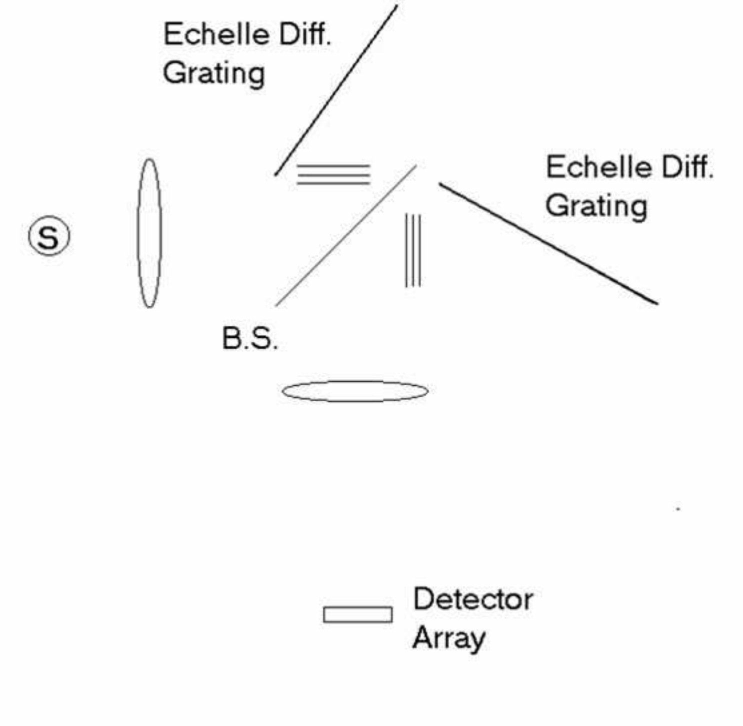

Fig. 1.— Schematic of a SHS with a transmitting beamsplitter.

issues specific to a broadband, high resolution SHS in the VUV.

A very coarse grating is needed to efficiently exploit the square or nearly square format of a CCD camera. We chose replicas of an existing echelle master grating. Our 23.2 groove/mm, 63.5 degree blaze gratings operate in 511th order for wavelengths near 151 nm. The separation of adjacent order (horizontal) fringes in a symmetric interferogram requires at least 4x511 pixels. Our choice of diffraction grating is thus compatible with 2048x2048 pixel CCD camera for wavelengths down to 151 nm. We chose the Princeton Instruments “Pixus” 2K by 2K VUV CCD camera.

The echelle gratings of our Mark 1 SHS have ruled areas of 46 mm x 96 mm. This size grating yields a theoretical limit of resolution of 0.058cm^{-1} (the inverse of the maximum path difference of 2 x 9.6 cm x sin 63.5°) with a symmetric interferogram and a smaller limit with an asymmetric interferogram. The theoretical resolving power at 151 nm is thus $>$ 1,000,000, and is $>$ 500,000 with an entrance aperture opened to maximize the luminosity-resolution product.

In order to approach these very high resolving powers over large spectral ranges, it is essential that the imaging of fringes onto the CCD be nearly free of aberrations. Interferometric quality mirrors are essential. Astigmatism is the most serious Seidel aberration and it arises both from the beamsplitter and from the off axis mirror(s) used to image the fringes onto the CCD. Mirror astigmatism must be controlled by limiting the mirror tip angle, by using non spherical mirror, or by compensating with more than one mirror. Aberrations have been calculated and included in our design. The highest fringe frequencies occur $\frac{1}{2}$ way between echelle grating orders. We are anticipating some loss of fringe contrast and thus sensitivity at the highest fringe frequency due to residual aberrations and "blooming" between CCD pixels. It is possible that some of the resolving power of our Mark 1 SHS will be sacrificed in order to reduce the sensitivity roll-off between orders. This can be done by modifying the image size on the CCD to over-sample the interferogram as needed.

Traditional phase correction as well as phase distortion issues in SHS instruments were discussed by Englert et al. (2004). Optical imperfections including distortion of the image on the CCD, a lack of perfectly flat grating surfaces, and a lack of a perfectly flat or homogeneous beamsplitter all lead to phase distortion errors in the interferogram. One of the advantages of SHS's is that fringes, curved by optical defects, can be straightened using software. Although software corrections can be convenient and cost effective in an SHS instrument with a narrow spectral coverage, much more effort will be required to map the phase errors of a broadband SHS. For that reason, we have devoted substantial effort and resources to minimizing phase errors (eg. with very high quality optics and proper optical mounts) and to maximizing phase stability of the Mark 1 SHS. Long term phase stability of the SHS is essential if the phase distortion map is to be used for correction of interferograms over an extended period of time. An all Invar, vacuum compatible, custom optical breadboard provides the base of the Mark 1 SHS. Additional Invar "sandwich" plates secure the top and bottom of the beamsplitter and diffraction grating mounts. The remaining aluminum parts of the beam splitter mount and grating mounts have been temperature compensated. Vacuum compatible "picomotors" are used to adjust the critical optics during operation.

Figure 2 is one the first interferograms recorded with the Mark 1 SHS using a monochromatic source. The straight and equally spaced fringes are encouraging. Figure 3 is a plot of every 4 row of a 2 dimensional Fourier transform from one of the Mark 1 SHS interferograms. The fidelity of the instrument is confirmed by the sharp (1 pixel wide) peak of the transformed spectrum.

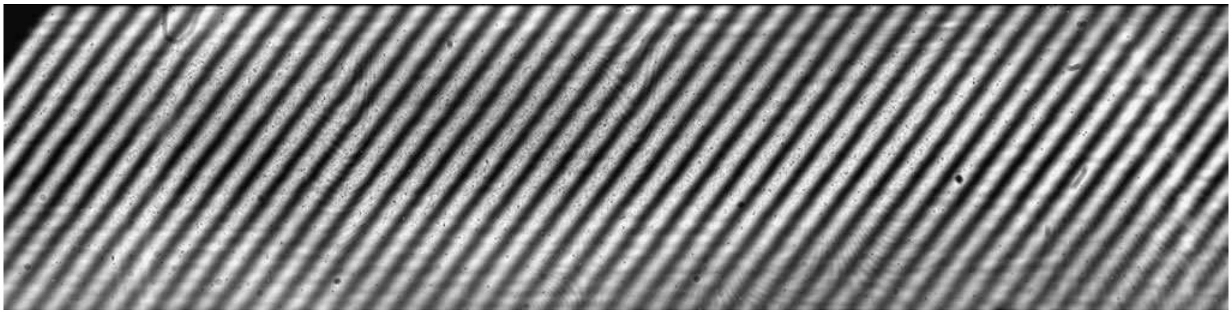

Fig. 2.— Interferogram of a monochromatic source from the Mark 1 SHS.

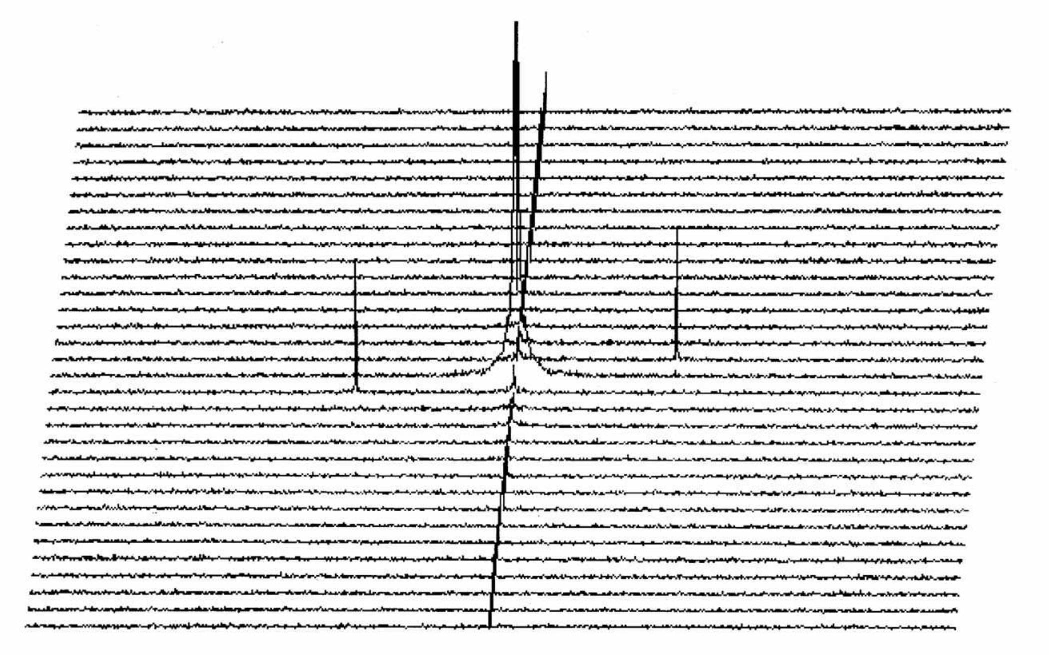

Fig. 3.— Transformed spectrum of a monochromatic source from the Mark 1 SHS.

3. The Mark 2 SHS

All reflection SHS instruments use a diffraction grating as a beam splitter and combiner (Harlander and Roesler 1990). The robust "ring" design is very stable due to the common path (Harlander and Roesler 1990). Several all reflection SHS's have been built and are now being used, but a very broadband instrument of this type has not yet been built. A special coarse diffraction grating with a symmetric blaze at low angle is needed to construct an all reflection, high resolution SHS with very broad spectral coverage. This will require a new master ruling.

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REFERENCES

Harlander, J. & Roesler, F. L. 1990, "Spatial heterodyne spectroscopy: A novel interferometric technique for ground based and space astronomy", Instrumentation in Astronomy VIII, ed. D. L. Crawford (Proc. SPIE, 1235), 622

Englert, C. R., Harlander, J. M., Cardon, J. G., & Roesler, F. L. 2004, Appl. Opts., 43, 6680