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Low dispersion ultraviolet spectropolarimeter for astrobiological research

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ABSTRACT

For the remote detection of chiral amino acids to be feasible, it is required to develop a high sensitivity spectropolarimeter susceptible to detect the signature of the Optical Rotatory Dispersion (ORD) produced by alanine in the 160-200 nm spectral range. This instrument is part of the payload of the *Ultraviolet Researcher to Investigate the Emergence of Life* (URIEL), a small size (50 cm primary) space telescope designed to carry out low dispersion (600-1,000) UV spectropolarimetry in the 140-350 nm spectral range. In this contribution, we describe the design of the spectropolarimeter.

Keywords: Space instruments, Ultraviolet optics, Spectropolarimetry

1. INTRODUCTION

Amino acids are the building blocks of proteins, the biomolecules which provide cellular structure and function to all living organisms on Earth. Though laboratory experiments have shown that amino acids may grow efficiently in interstellar ices, the only conclusive detection in space comes from the detection of glycine in the gaseous envelope of comet 67P/Churyumov-Gerasimenko by the ESA's Rosetta mission[1].

The detection of amino acids in space bodies is hampered by contamination problems and the enormous resources required to reach the surface of even the nearest Solar System bodies. The development of new means and technologies for their remote detection is crucial for astrobiology. For this reason, there have been numerous attempts to detect glycine, the most abundant amino acid in space ices, at radio wavelengths. Unfortunately, the efforts have been fruitless so far[2-5] because of the intrinsic weakness of the lines and the confusion with the spectral signatures from the large number of species in protostellar cores[6].

The expected abundance of alanine, the second most abundant amino acid, is lower but still high (alanine to glycine abundance is consistently found to be ~0.4 in laboratory experiments[7,8]) and alanine has the advantage of being a chiral molecule, i.e., alanine can be detected through its imprint in the polarization spectrum; any abundance imbalance between the two optical isomers results in the polarization of radiation at the wavelengths where the structural differences are the largest which is at 180nm for alanine. The strength and properties of the polarization signal depends on the abundance and relative concentration of the enantiomers along the line of sight. A recent study based on the data obtained from the analysis of meteoritic samples estimates that the optical activity of alanine may result in an increase of up to 40arcmin in the rotation angle of the lineal polarization at 190nm produced by the optical phenomenon known as Ordinary Rotary Dispersion or ORD[9] (see Figure 1). If the impinging radiation is linearly polarized, the ORD produces a rotation, [α], of the plane of polarization that depends linearly on the enantiomeric imbalance as shown in Figure 2. Non-racemic mixtures also induce fractional circular polarization on unpolarized incident light that it is comparable in magnitude to the differential absorbance used for this plot. This technique has been successfully used in the lab to detect photosynthetic microbes[10].

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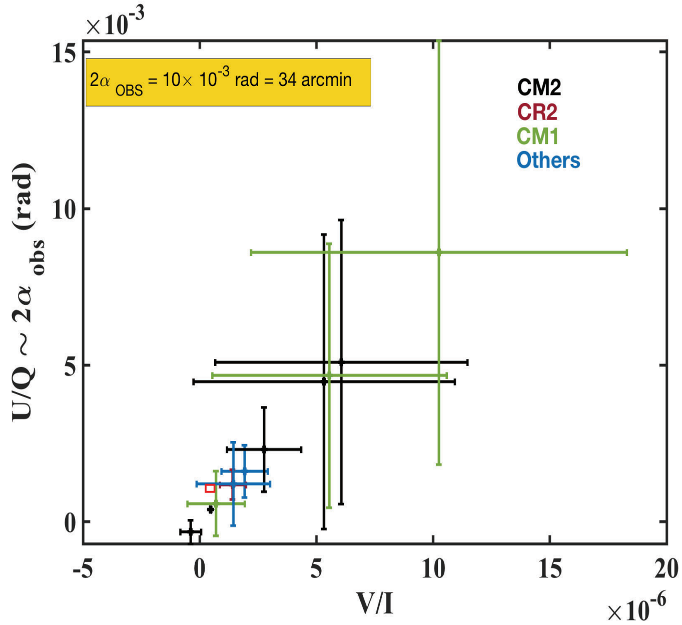

Figure 1: Calculation of the Stokes parameters[9] of UV radiation after propagating through a non-racemic mixture of alanine with density and enantiomeric imbalance like the observed in the meteorites[11]. The Stokes parameter U, Q, V and I measure the polarization of the outgoing radiation with intensity I; U and Q measure the linear polarization in perpendicular planes and V the circular polarization.

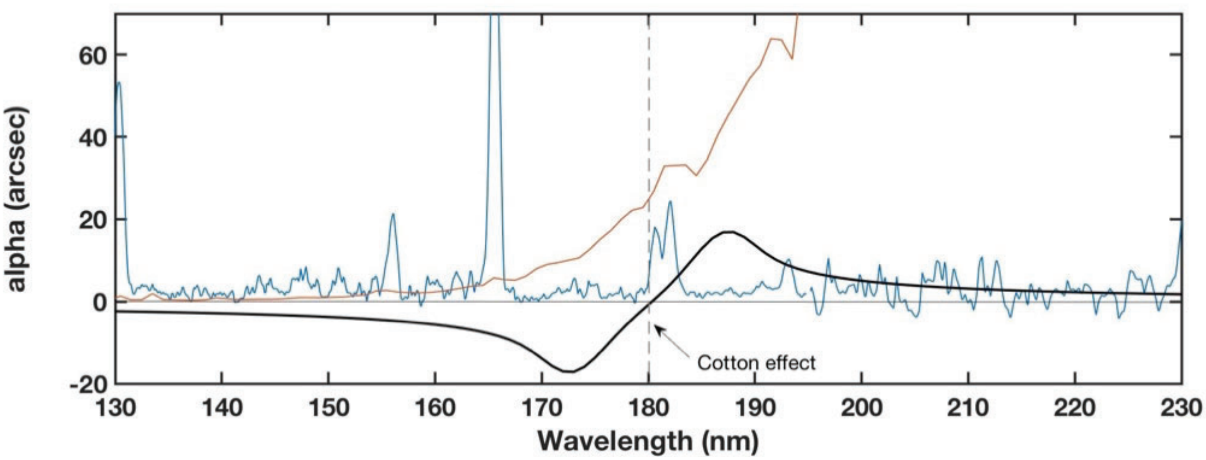

Figure 2: Illustration of the expected ORD (α) for an enantiomeric excess of 0.1[9] (black). The strength of the ORD is evaluated assuming a relative abundance of alanine to glycine of 0.4 (in number of molecules) and using an abundance of glycine of 170 ppb, which is the measured by Rosetta in comet C67/Churyumov-Gerasimenko[12]. For comparison, the spectra of Comet Bradley (blue) and the Sun (red) are displayed to show were the ORD signal would be detected in the spectrum; these energy distributions are shown in arbitrary units.

The high sensitivity of the spectropolarimeter capable of detecting the signature of alanine in nearby Solar System bodies will also enable unique capabilities for the investigation of the distribution and properties of molecules and small particles in exoplanetary systems, at the time of planetary building-up. Though thousands of planetary systems are being formed within 500 pc of the Sun, little is known about the processes involved in the dissipation of the disc, the formation of the planets and the generation of swarms of comets. Spectropolarimetry is a unique tool for this study since it exploits all the information carried by the electromagnetic waves. The unpolarized stellar radiation is scattered by the large molecules and dust particles in the circumstellar environment and becomes polarized. The degree and direction of polarization of this light depends on the microphysical properties of the scatterers (composition, shape, size distribution) and their abundance as well as on the geometry of the system and the wavelength of observation. Indeed, the state of polarization of the scattered light has been shown to be much more sensitive to particle properties than the intensity of the scattered light.

With this science case in mind, the concept for the mission URIEL (Ultraviolet Researcher to Investigate the Emergence of Life) was born[13]. The optical design of the spectropolarimeter was adapted to fulfill the scientific requirements of these two main science cases.

2. OPTICAL DESIGN

The spectropolarimeter is designed to operate in the 140 nm – 350 nm spectral band. The main purpose of the instrument is to perform spectrally resolved full Stokes polarimetry with high accuracy, at least 1000 ppm, and with optimal performance in the 160 nm – 200 nm spectral region. The payload is constituted by the following optical modules:

- Ritchey-Chrétien telescope, with a 50cm aperture.
- Polarimeter based on a rotating QWP (8 positions) + Wollaston prism. Both polarizations provided by the prism are sensed simultaneously at the detector.
- Offner spectrograph with a convex 600 lines/mm grating.

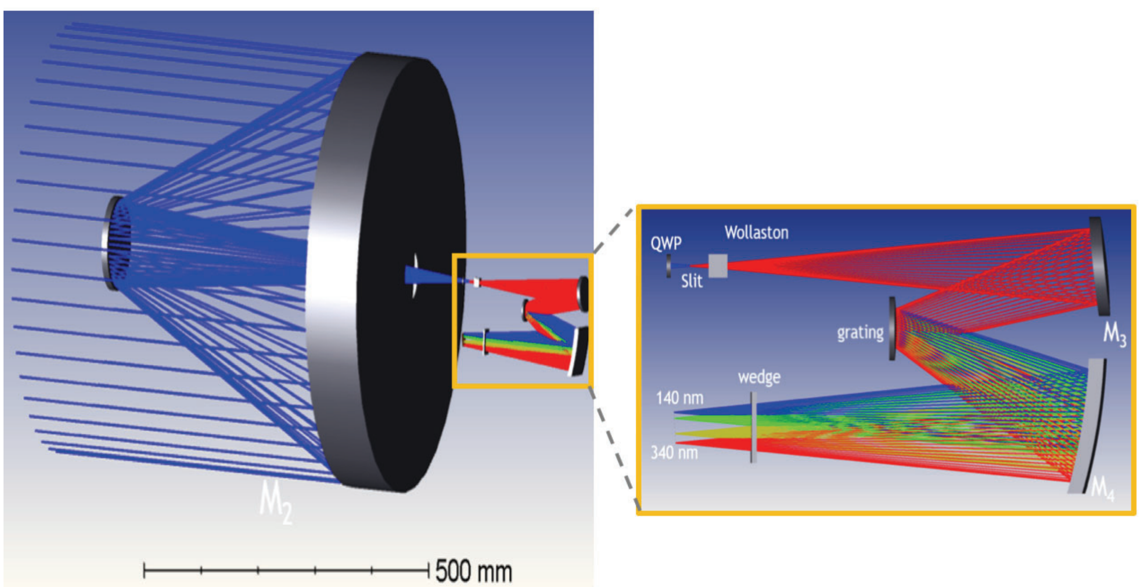

Figure 3: Optical design of the UV telescope and the spectropolarimeter (left). The optical design of the spectropolameter is magnified in the inset on the right

The structure of the spectropolarimeter is based on a carbon fiber composite and the mirrors are made in Zerodur. All refractive elements will be manufactured in MgF_2. The system has been preliminarily designed to operate with a CCD201-20 EM CCD detector from e2v-teledyne, well suited for the detection of weak signals. The sensor length is around 13 mm (i.e. 1024 pixels x 13 microns). The proposed optical system is displayed in Figure 3. By design, the system provides a couple of spatially resolved spots (separation equal to 400 microns) per wavelength, corresponding to ordinary and extraordinary beams on passage through the Wollaston prism. The broad spectral coverage required, 140-350 nm, results on the maximum wavelength being more than twice the minimum one and as we are using a grating as dispersive element, some mode overlapping is unavoidable in the 280 nm - 350 nm. To solve this issue, a wedge with a slight angle of 2^o has been included to separate diffraction orders +1 and +2 at the detector.

The Figure 4 shows the arrangement of light spots at the detector in the spectral region around 280 nm. Red and yellow spots in the figure, corresponding to the first order of diffraction, will be processed jointly, whereas second order of diffraction spots (much less bright, due to the effect of blazing in the grating) will be typically discarded. As shown in the left panel, the system is capable of discriminating wavelengths as close as 0.3nm in the 180nm region, and resolving powers of 600 (and up to 1,000) are considered feasible once the design is fully optimized.

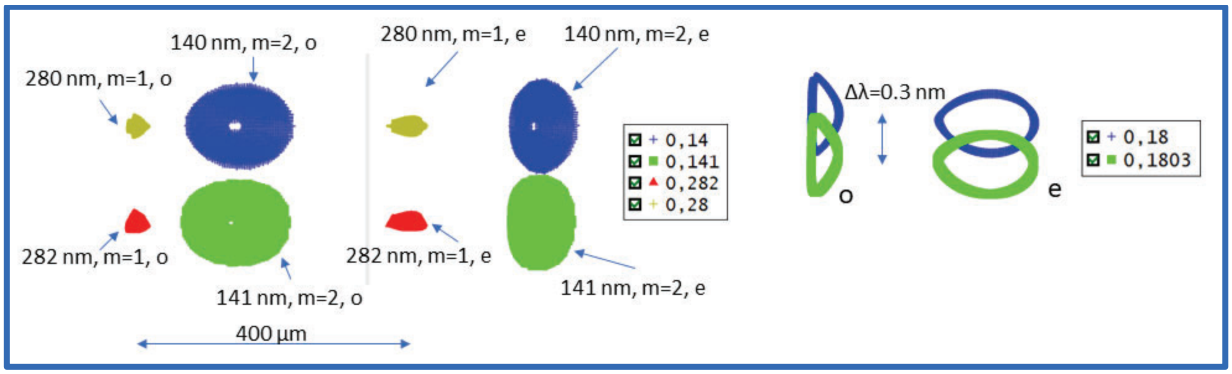

Figure 4: URIEL arrangement of light spots at the detector in the spectral region around 280 nm

The main purpose of the payload is to perform spectrally resolved full Stokes polarimetry, with particular emphasis around the 180nm spectral region. Some graphs representing the polarimetric capability of the instrument are displayed in Figure 5. In the left panel is shown the polarization pupil map after light passage through the telescope, for input linear polarized light at 45°. The exit light maintains the input polarization unless for some very marginal elliptical polarization at the edge of the pupil. Graphs at the right panel show a simulation of the expected modulation signals that will be obtained through rotation of the QWP, for fully polarized light with Stokes parameters Q, U and V. The last graph shows the expected difference in signal corresponding to a 10 arcmin rotation on the polarization angle, for light with a 1% degree of linear polarization.

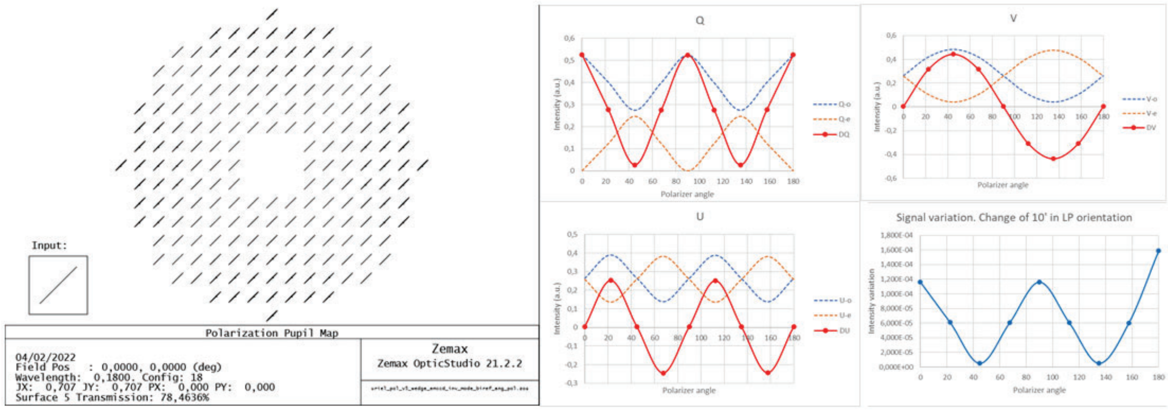

Figure 5: Polarization pupil map and expected Stokes parameters.

4. SUMMARY AND CONCLUSIONS

The current design is robust from the opto-mechanical point of view and suitable to detect rotations of the polarization plane of 10 arcmin for levels of polarization as low as 1% thus, it is well suited to study the evolution and distribution of circumstellar material in young planetary discs. It needs however, to be improved to reach similar accuracies for polarizations of 0.1%. It will also need to be adapted for the observation of extended sources such as comets to prevent the intermixing of elements of the Stokes four-vector as a result of the jitter of the space telescope. This is a well-known problem in the context of Solar research that has been technically solved by the CLASP[14,15] project at the more demanding wavelength of the Lyman-α line, 122 nm.

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