SF2A 2015
F. Martins, S. Boissier, V. Buat, L. Cambrésy and P. Petit (eds)

DIFFRACTIVE TELESCOPE FOR PROTOPLANETARY DISKS STUDY IN UV

W. Roux[1] and L. Koechlin[1]

Abstract.
The direct observation of exoplanetary systems and their environment remains a technological challenge: on the one hand, because of the weak luminosity of objects surrounding the central star, and on the other hand, because of their small size compared to the distance from Earth. The fresnel imager is a concept of space telescope based on focusing by diffraction, developed by our team in Institut de Recherche en Astrophysique et Planétologie (IRAP). Its high photometric dynamics and its low angular resolution make it a competitive candidate. Currently we propose a space mission on board the International Space Station (ISS), observing in the ultraviolet band, in order to validate its capabilities in space and so increase the Technological Readiness Level (TRL), anticipating a larger mission in the future. To reach this goal, we have to provide some evolutions, like improving the design of Fresnel arrays or conceive a new chromatism corrector. This paper presents the evolutions for the ISS prototype and its possible applications like protoplanetary disks imaging.

Keywords: Fresnel Imager, Diffractive telescope, UV astronomy, Protoplanetary disks imaging

1 Introduction

Nowadays, space telescopes are necessary to overcome the Earth atmosphere and observe the Universe, especially in the ultraviolet band. But the weight and size of large focusing systems limit the launch opportunities, thus limiting the field and resolution of available missions. The Fresnel Imager is an innovating alternative to classical optics to avoid these drawbacks, and could be a serious candidate for future missions. This project uses "Fresnel arrays" as primary optics to make images.

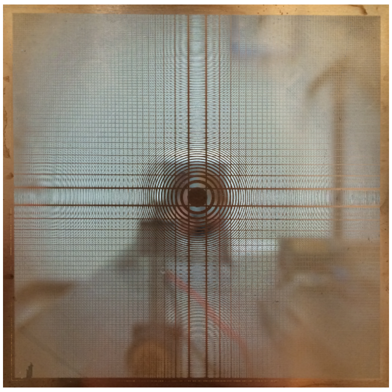

Fig. 1. Last Fresnel array engraved, used for tests in the UV-band. Its focal length is $12.695m$ for $\lambda = 260nm$ ($c = 0.65m$ and $N = 160$).

The Fresnel arrays use the principle of Fresnel zone plates, with the particularity that the pattern is not printed on a transmissive surface but directly engraved in a solid surface (Fig. 1). There is a cophasing relation between each rings, as first experienced by Soret (1875). Thanks to this design, a plane wavefront is made

---

[1] IRAP, CNRS, Université Paul Sabatier, 14 avenue Edouard Belin 31400 Toulouse, France

spherical and thus focused by diffraction through the numerous void holes in a Fresnel array, so the light is not affected by an optical material that would be present in classical optics.

Actually, with a Fresnel diffractive array made of thin metalized foil, a large aperture around a few meters, the primary system weights about a kilogram. Further than weight, this system is tolerant in terms of manufacturing and positioning (L. Koechlin et al. 2005). Its angular resolution is limited by the aperture, same as classical optics, the width of the point spread function (PSF) is inversely proportional to the diameter of the Fresnel arrays. This system provides a high contrast on compact objects, that is necessary to observe the environment of protoplanetary disks.

Like any optical systems, there are some drawbacks, but they can be corrected by an adapted design. First the chromatism inducing by the fresnel arrays. Actually the focal length is wavelength dependent, so there is a series of focal planes along the optical axis. The system requires a Fresnel blazed lens placed in a pupil plane to correct this dispersion, so currently we are working on a Fresnel blazed mirror (like described below). Our previous design was not adapted to UV and would have caused transmission loss through the optical material. The focal length is also quite long for large apertures because it follows: $f = D^2/(8 * N * \lambda)$, where D is the diameter of aperture, N the number of Fresnel zones, and λ the wavelength. For instance, if we observe at the Lyman-α line ($\lambda = 121nm$), with an aperture $D = 6m$ and $N = 2000$ Fresnel zones, the focal length is $f = 16.6km$. That is why a nominal mission, like studied with Centre National d'Études Spatiales (CNES) from 2008 to 2010 (Hinglais 2011) requires a formation flying (Fig. 2). A first module holds the Fresnel array, and a second one contains the field optics, the chromatism corrector and the instrumentation required for image acquisition, like spectro-imagers and high contrast cameras. Both these modules can be launched by a single Soyuz and placed in orbit around the second Lagrangian point for a 5 year mission (Raksasataya et al. 2010).

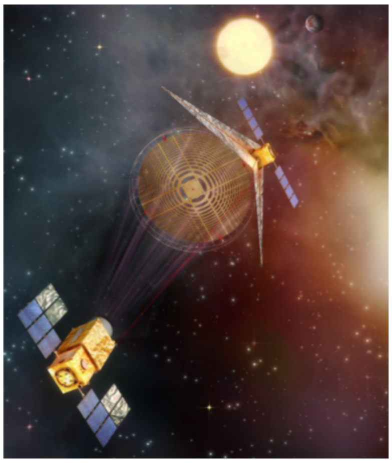

Fig. 2. Artistic view of a possible nominal mission, with the two modules in formation flight: the Fresnel array and the receptor module. (Credit: CNES/GEKO 2008)

2 Future evolutions and probatory mission

Since the presentation of the new developments on the Fresnel Diffractive Imager project at COSPAR Moscow in 2014, we have new leads for a probatory mission on the ISS.

2.1 A new chromatism corrector

We want to replace of the Fresnel blazed lens in the previous prototypes by a Fresnel blazed mirror, to prevent diffusion or transmission loss through fused silica, and so improve the quality of our instrument. This mirror could get an additive concavity to replace the last lens, used for final image focusing. We have calculated this new profile for chromatism correction by reflection. Currently we are investigating what would be the best way to produce this optical element. The previous Fresnel lens was engraved by photolithography, but this method presents some constraints for manufacturing. That's why we are prospecting several companies to engrave this piece with ultraprecision machine systems supporting single point diamond lathing. This new blazed concave grating will be the subject of a future article.

2.2 A new holding bars layout

Until now all Fresnel arrays produced feature a pseudoperiodic bars system to hold the rings in place. As we can see on Fig. 1, there are orthogonal bars every 3 rings. Preliminary studies have shown that regular and equidistant bars could reduce stray light and so raise the dynamic range, but we will make further simulations to enhance these studies. Currently we are developing a new simulation program of light propagation through our instrument to improve the PSF quality, using the new configuration of our prototype.

2.3 New optical tests in the ultraviolet

Due to the new equipment we will produce for the Fresnel Imager, we need a new measurements campaign. Moreover, the last tests in the ultraviolet were not optimal because the CCD camera with a UV sensitive cathode available at the time was not performant in terms of contrast. In February 2015, we met a research team at the Institute for Astronomy and Astrophysics from University of Tübingen in Germany, they work with and develop microchannel plate amplifiers and resistive anode detectors dedicated to UV, and we agreed to work together on a new tests campaign for the Fresnel imager.

2.4 The probatory mission on ISS

The probatory mission on the ISS that we propose consists of two parts on the extremities of the Integrated Truss Structure. The first one consists of the Fresnel array and an orientable mirror that will be used to aim astrophysical targets in the sky, and to compensate the drift of the ISS as well as stabilize images in case of vibrations. The resolution would be $0.15 arcseconds$ for an aperture between 15 and $20cm$. Recently, an agreement of collaboration has been signed with the Institute of Astronomy of the Russian Accademy of Sciences (INASAN), the Universidad Complutense de Madrid (UCM) and the Université Paul Sabatier (UPS) to prepare the future scientific program that would be required for a such mission, and the mission proposal to the Russian space agency ROCOSMOS taking into account the technical constraints.

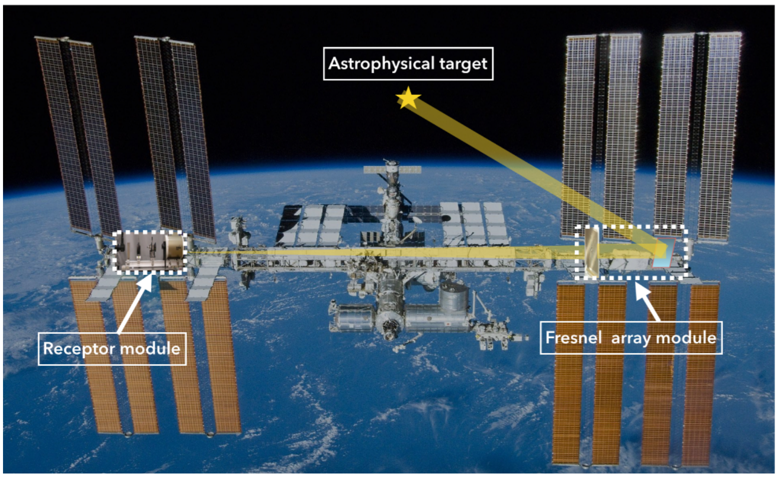

Fig. 3. Scheme of the possible configuration of our prototype on the ISS (Credit: NASA/Crew of STS-132).

3 Science cases in the UV

Due to the capacity of the Fresnel Imager to focus the light by diffraction, with no optical material in the light path, this instrument is more competitive for UV. Actually optical materials scatter and limit the transmission for these wavelengths. The shorter is the wavelength, the more difficult is the challenge. Moreover, the optics can be contaminated by deposited materials on their surface and become opaque to UV.

The UV astronomy is a recent domain of observation because the Earth atmosphere becomes opaque below $320nm$. The interstellar medium becomes opaque anyway below 91.2nm due to the Lyman cutoff, so the observable wavelength domain is limited even from space. The most interesting wavelength to observe with the proposed mission is Lyman-α ($\lambda = 121.6nm$). It corresponds to the most energetic electronic transition in the hydrogen atom. This choice will allow to map the repartition of high energy hydrogen, to examine hot stars environments and stellar formation areas for instance, and the Universe in general but limited to our neighborhood because of the redshift. We could observe numerous other spectral lines in the UV (including life signatures on exoplanets) but for budgetary reasons we will limit to one or two spectral bands for the probatory mission, and up to three ones for a nominal mission.

3.1 Protoplanetary disks

The protoplanetary disks are composed of dust and gas orbiting a central star. There are two main sources of UV in a protoplanetary disk (Gómez de Castro 2011). The first is molecular hydrogen in the inner hot gas disk that radiates in Lyman-α, excited by the UV from the central star. The second ones are the accretion shocks, emitting intense UV and X-rays when the matter from the gas disk meets the magnetosphere of the star and hits its surface (Fig. 4).

The imaging of protoplanetary disks is interesting for the study of matter distribution around them and its gravitational drive, to predict their evolutions. That could inform on the role of UV on the disk evolution because we know that UV and X-rays evaporate and blast away the upper and the lower disk surfaces. These studies requires imaging and spectro-imaging at very high angular resolution and contrasts, reachable by a Fresnel Imager with a large aperture.

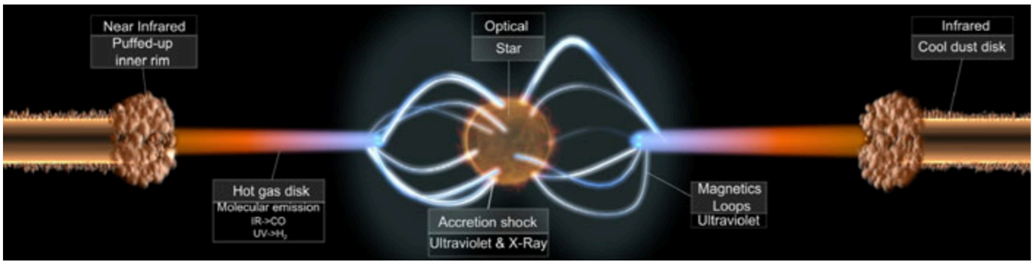

Fig. 4. Representation of the different UV sources in a protoplanetary disk (Credit: A.I. Goméz de Castro).

3.2 Other science cases

The study of other astrophysical disks helps to understand the physics behind their formations and evolutions. For instance Active Nucleus Galaxies (AGNs) and quasars (QSOs) present accretion disks orbiting around supermassive black holes, radiating in the UV by thermal emission. Some white dwarfs can also have an accretion disk emitting in the UV.

4 Conclusions

These new leads to improve the Fresnel Diffractive Imager have driven us to build up new collaborations with diverse institutes from Europe and Russia. We except to have results within two or three years with the acceptance of the probatory mission, which will then increase the TRL, provide a modest but valuable scientific return, and allow to prepare a nominal mission. In parallel the reachable science cases will be thoroughly prepared and well defined.

References

Gómez de Castro, A. 2011, Experimental Astronomy, 30, 205

Hinglais, E. 2011, Experimental Astronomy, 30, 85

L. Koechlin, D. Serre, & P. Duchon. 2005, A&A, 443, 709

Raksasataya, T., Deba, P., Rivet, J. P., et al. 2010, Proc. SPIE, 7732, 77322D

Soret, J.-L. 1875, Archive des sciences physiques et naturelles, 52, 320