PRINCIPLE OF A COAXIAL ACHROMATIC INTERFERO CORONAGRAPH

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Abstract. We describe here the principle of a new type of coronagraph, based on the incident flux division with pupil reversal and phase shift on one beam, then recombination with destructive interferences at the center orf the field. This concept of nulling has already been used in the Interferometrical Achromatic Interfero-Coronagraph (AIC, Gay & Rabbia 1996), which lies on a Michelson interferometer interferomùetry which does not allow an easy insertion in the focal facility of a telescope. The variant under consideration has a completely coaxial design with an original and very compact optical combination. It is based upon two coaxial thick lenses in the same medium, stuck one to each other with a very narrow gap in between and a proper coating of the interfaces. The very geometry of the device ensures moreover the permanent and rigorous cophasing of the interferometer. The optical combination which fulfills this problem is unique and presents a range of properties which ease its insertion in the focal instrumentation of existing telescopes or next generation ones.

1   Introduction

The detection of faint objects near bright astrophysical sources requires both a high angular resolution and a high dynamic range. One of the promising techniques to increase the dynamics is to use of stellar coronagraph. The word "coronagraph" has been introduced by B. Lyot (1931) for an instrument he designed to observe the solar corona. It is intended to suppress most of the light from the bright source in order to make the faint one visible.

A coronagraph enhancing the dynamic range could be a powerful instrument for a variety of astrophysical topics. In stellar physics, one could detect companions like low-mass stars, white or brown dwarfs, and also dust shells around asymptotic giant branch (AGB) and post-AGB stars, protoplanetary disks, or even

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the extended counterpart of the accretion disk of young stellar systems. In the field of extragalactic astrophysics, this technique can greatly contribute to a better understanding of the structure (torus, disk, jets, starforming regions, etc.) and dynamical processes present in the vicinity of active galaxy nuclei. The last example is related to the problem of the direct imaging of extrasolar planets, a question which is now becoming of paramount importance. In this context, a coronagraphic device appears absolutely mandatory since the contrast between the star and an orbiting planet is tremendous.

Several stellar coronagraphs have been derived from Lyot's model, lying on an opaque amplitude mask in the focal plane, combined with a stop at the relayed pupil. For example, Roddier & Roddier (1997) have proposed a coronagraph using a phase mask introducing a π phase shift, producing a self cancellation of the stellar light by destructive interferences. The Four Quadrant Phase Mask Coronagraph proposed by Rouan et $al.$ (2000), has already produced very interesting and promising results.

Achromatic Interfero-Coronagraph (AIC) is based on a fundamantally different principle. Indeed it does not introduce any discontinuity in the image plane. The basic configuration is the Michelson's interferometer. The incoming flux is separated into two parts by a beam-splitter. One of the two beams passes threw a cat's eye device which reverses the pupil and introduces an achromatic π phase-shift by focus crossing (Gouÿ, 18xx). The second beam however travels the same optical length but does without pupil reversal and phase shift. Both beams are recombined by the beam-splitter. Destructive interference occurs for those points that are invariant through the pupil reversal, that is the center of the field. So, the light of an on-axis object is ideally perfectly rejected. On the contrary, an off-axis object does not interfere with its symmetric part. The standard AIC presents the drawback to deliver its output beam orthogonal to its input beam. Its insertion in an existing environment thus requires extra optical components potentially adding defects and flux loss.

The "CIAXE" (standing for "$Coronagraphe$ $Interférentiel$ $Achromatique$ $dans$ $l'aXE$") we describe hereafter derives from the standard AIC, but with an original, fully coaxial and compact optical combination. It involves only two coaxial thick lenses with proper geometry and coating which is more compact and much easier to insert at the focus of a foacl instrument.

2 Principle of the CIAXE

The optical combination is described Figure 1. The surface M_2 between the two thick lenses is half-reflecting. The surfaces M_1 and M_3 are fully reflecting except for small circular zones surrounding S_1 and S_3, respectively the input and output apertures. The incident beam coming from an on-axis source has to converge onto S_1, in the input aperture. Then, it reaches M_2 (which will be refered to as the "beam splitter" in the sequel) where it is divided into a transmitted beam and a reflected beam. The reflected beam reaches M_1, and is reflected so as to converge onto S_3 (through M_2). The transmitted beam reaches M_3 and is reflected so as
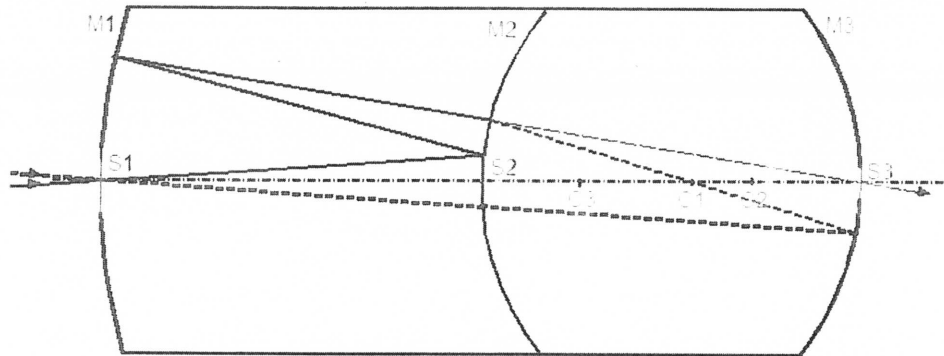
Fig. 1. Incoming beam from an on-axis source is converging onto S_1, the summit of the interface M_1. The optical surface is coated to be reflecting, except around S_1, so as to delimit the input field. The beam splitter M_2 sends light both on mirror M_1 (solid line) and on mirror M_3 (dotted line). The beam reflected by M_1 and then transmitted by M_2 converges onto S_3. The beam reflected by M_3 converges to a real image point C_1 on the optical axe, and is then reflected back by M_2 onto S_3. As the optical lengthes $S_1 S_2$ and $S_2 S_3$ are equal, these two waves interfere destructively before reaching the output aperture.

to converge onto a real "focus" $C1$, then reaches back M_2, which makes the beam converge onto S_3 at the center of the output aperture. The transmitted beam crosses the focus (C_1) and thus undergoes a π phase shift and a pupil reversal. The reflected beam howver does not cross any focus and therefore does not undergo any phase shift and pupil reversal. Provided the optical lengths are equal, both beams converging onto S_3 vanish by destructive interferences. The light of an on-axis object is therefore perfectly extinguished at the output, at least ideally.

An elementary calculation shows that there is only one suitable solution up to an arbitrary scale factor. Indeed, let us choose the common thickness of the two lenses as the length scale unit, then we have three free parameters which are the radii of the three optical surfaces (in term of this length scale unit). We also have three conditions to fulfil :

1. S_3 must be conjugated with S_1 by reflection on M_2, reflection on M_1, and transmission by M_2;

2. S_3 must be conjugated with S_1 by transmission by M_2, reflection on M_3, and reflection on M_2;

3. the magnifications of these two combinations must be opposed.

We now show that the system sends back to the entrance *all* the energy of the input beam from an on-axis source. Let us denote ($r = \sqrt{R}.e^{i\rho}$), and ($t = \sqrt{T}.e^{i\tau}$) the reflection and transmission coefficients of the amplitude through the beam splitter. the conservation of the energy in the beam-splitter (assumed to be non-absorbant) imposes the condition $\rho - \tau = \pi/2 + k\pi$ (see *e.g.* Gay & Rabbia 1996).
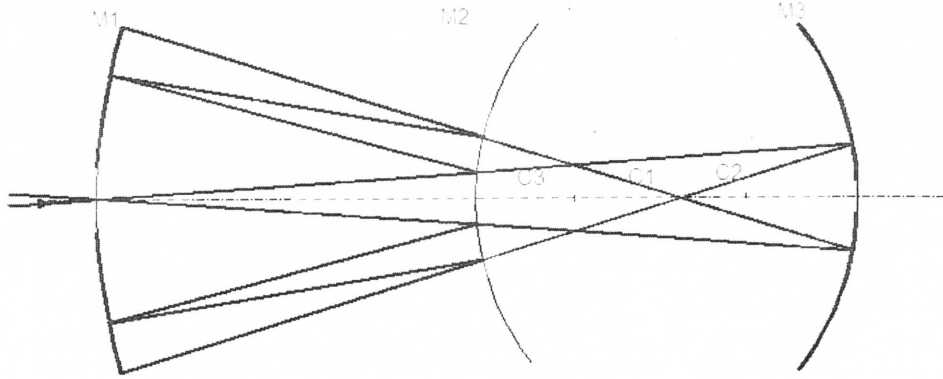
Fig. 2. Optical paths for input beams reflected or transmitted twice by the beam splitter. Energy is sent back towards the entrance after the amplitudes has been recombined and reflected by M_1.

Figure 2 displays the optical paths for the fractions of the input beam, which are respectively reflected twice and transmitted twice by the beam splitter. Both recombine, interfer additively and thus carry all the input energy towards M_1. Indeed, their amplitudes are respectively r^2 and $-t^2$, the minus sign coming from the focus crossing of the twice transmitted beam. The resulting light intensity thus reads:

$$|r^2 - t^2|^2 = \left|e^{2i\rho}\left[R - T.e^{2i(\tau-\rho)}\right]\right|^2 = |(R+T)e^{2i\rho}|^2 = 1 \qquad (2.1)$$

Since the recombined beam hits M_1 with zero incidence (because C_1 is the center of curvature of M_1), it is reflected back onto itself by M_1. Since the propagation of light is invariant through direction reversal (time reversal), then, this recombined and reflected beam comes back onto its own steps and reaches back the entrance, sending back the unwanted energy of an on-axis source towards the sky.

As an off-axis are not invariant through the pupil reversal, its splitted beams do not interfere one with each other and no rejection occurs. We end up two images of the faint objet which are symmetrical with respect to the axis of the coronagraph. Figure 3 displays the input beam for an off-axis object.

There could be many reflections inside the CIAXE that we do not describe in these proceedings. In all cases, for an ideal CIAXE, all the energy which comes from a source located on the axis of the coronagraph is sent back in entrance and half of the photons of an off-axis source are divided symmetrically around the extinguished main object in the image plane. If the beam splitter parameters R and T are not both equal to 0.5, there are additional secondary images after multiple reflections that superpose with first order images of an on-axis companion. The proportion of an off-axis source photons thus converges towards 50% in exit, even if the beam-splitter is not perfectly realized.
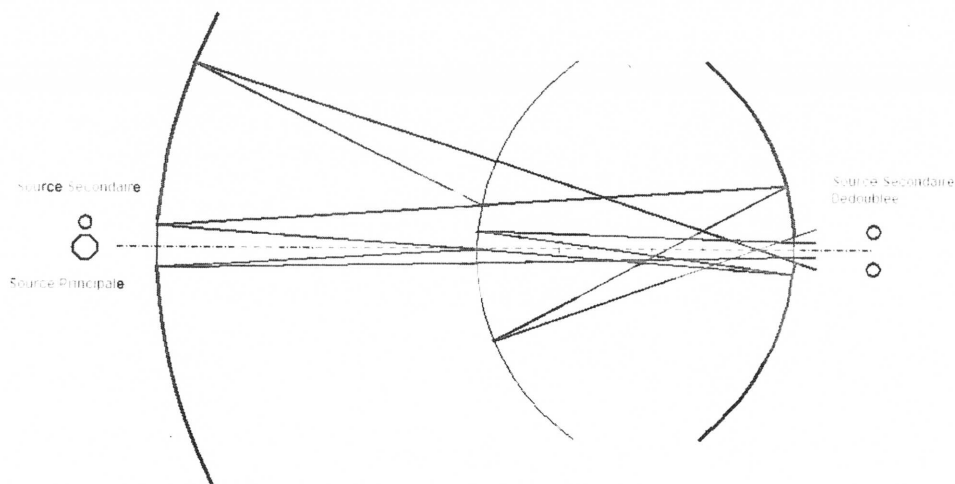
Fig. 3. Optical paths for an off-axis object : as the pupil is reversed, there is no coherent addition of beams transmitted and reflected once by the beam-splitter. The π-phased image appears symmetrically from the other one with respect to the axis of the coronagraph.

3   Performance Estimation and Discussion

Let us recall here the specificities and drawbacks of an extinction system involving division of the flux and pupil reversal. As pupil is reversed, it is twice as sensitive for odd order wave surface deformations, and insensitive for even order deformations. Tip-tilt being the main problem of atmospheric alteration, this singularity becomes a drawback without a really efficient adaptative optics system. The CIAXE has the particularity to duplicate the image of a companion, each replica having one fourth of the incident photons, but this issue can be an advantage for astrometry.

The optical system CIAXE presents a unique combination of properties. First of all, it is achromatic by construction. So, we can use it on a large spectral band which is only limited by the transmission of the medium. For the near infrared domain, one may build it in Zinc Selenium, which is an easy to machine material transparent in a large spectral band. The CIAXE does not introduce any discontinuity in the treatment of the wave surface and does not require any pupil re-imaging. This system allows in principle the detection of a really close companion, around one third of the first dark Airy ring, *i.e.* 0.4 λ/d.

It is also a passive system composed of only two cylindrical optical components with only spherical (or quasi-spherical) active surfaces, without any mobile part. Moreover, it is easily removable to take a direct image of the source, or commutable with another device. We can select its scale factor, as its properties do not change through homothetic transformations.

The quality of extinction of the coronagraph relies on the correction of the spherical aberration caused by M_1 and M_3 optical surfaces. That correction is more and more important as we are working with an opened beam. A simulation for an ideal system with just the M_3 optical surface aspherised with a conicity coefficient of 0.6 gives a rejection rate superior to 10^6 (15 magnitudes) (ratio of the energy of an object on-axis at the input to the energy of the same object at the output). The real performance of such a coronagraph will depend on the quality of its realization. Our estimations with the quality of new machining processes allow us to believe that the loss in rejection rate, as compared to its theoretical performance, would be less than two decades, *i.e.* 10 magnitudes of rejection.

4   Conclusion

The optical system CIAXE works theoretically as a perfect coronagraph and presents a unique range of properties ensuring optimal extinction. Its achromaticity makes these performances available on a large spectral band. This system is easy to insert, commute or remove in the focal instrumentation of a single-pupil telescope. Additionnal studies and numerical simulations will be necessary to evaluate the limits of such a coronagraph for a ground-based telescope equipped with adaptive optics. The CIAXE could be efficiently used for multi-pupil recombination, as it keeps its range of qualities and has the totallity of incoming faint object photons. The qualities of wave surface treatment of this no-mask coronagraph and the relative simplicity of the optical pieces allow us to believe thet the CIAXE will match the ambitions of present and future projects requiring coronagraphy.

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