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INTERFEROMETRIC NULLER USING THE ACHROMATIC INTERFERO CORONAGRAPH

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Abstract. Among the various recombination schemes devised for nulling interferometry, one is to use the Achromatic Interfero Coronograph (AIC) which basically is a modified Michelson-Fourier interferometer made compact by cementing together optical components. The principle of this AIC is based on the focus-crossing property, from which a wave of light experiences an achromatic π phase shift when crossing a focus. Operated up to now only on a single telescope, this device is able to accomodate several beams for nulling. We describe the use of AIC as an interferometric nuller for a two-aperture interferometer.

1 Nulling Interferometry

Starlight prevents observation of its angularly-close environment because of both the angular limit for close-sensing (diffraction limit) and the tremendously large ratio (star brightness)/(environment brightness). Coronagraphy aims at recording images in which starlight is removed. Interfero-Coronagraphs (in other words those based on removal of starlight by destructive interferences) can explore the environment of the star at (or at better than) the diffraction limit set by the telescope's diameter and the wavelength used (Rabbia 2003). Even so, sensitivity is not sufficient to see as close a companion as a planet. Thanks to the significantly higher angular resolution it provides, Nulling Interferometry (NI from now) goes closer to the star.

Basically, NI (Bracewell 1978) achieves extinction of starlight (on-axis source) from a destructive interferences process obtained by inserting a π phase shift between the couple of waves collected by the interferometer. As far as possible the

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destructive interference (rejection process) must be achromatic, in order to use the largest possible spectral bandwidth and so to increase the signal from the companion and to make available a spectral analysis of its radiation. The instrument basically works as a spatial filter, projecting its spatial response against the sky (see Fig. 1) from which star's contribution is removed while companion's contribution is transmitted.

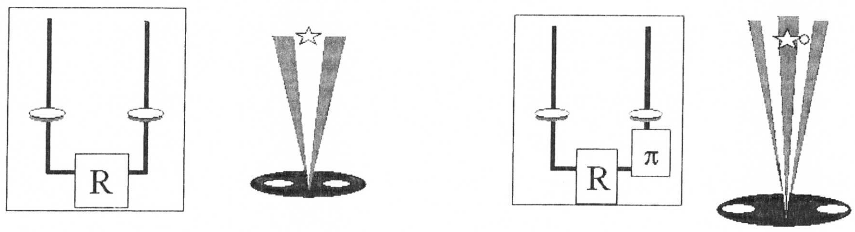

Fig. 1. *Left*: conventional stellar interferometry, with projected fringe pattern exhibiting a bright fringe (full transmission)on-axis. *Right*: nulling interferometry, on-axis source is obscured by the reversed pattern (dark fringe on-axis) while companion is transmitted when the baseline is adjusted to set a bright fringe conveniently.

2 A Key-Component

Achieving the required phase shift is the heart of NI and it is the duty of the Achromatic Phase Shifter (APS), which thus appears as a key-component. Various APS's concepts have been devised (Rabbia *et al.* 2002a). The APS's devices use the two interferometric arms separately, to eventually achieve the required ($\phi 1 - \phi 2$) phase shift, which can be π or $\pi/2$ depending on the recombination scheme. Downstream, the light meets a beam recombiner device feeding the detector, to record either a fringe pattern or a flat tint, as usually found in interferometry (Rabbia 2003) In the latter case, $\pi/2$ is the needed phase shift, because an extra $\pi/2$ phase shift is added by the beamsplitter.

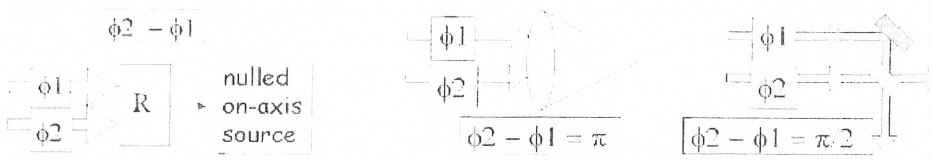

Fig. 2. *Left*: the making of the required phase shift. Center: fringe mode recombination (multi-axial scheme). *Right*: flat-tint mode recombination (mono-axial scheme).

3 AIC: A Coronagraph and a Nuller-Recombiner

3.1 Regular AIC in Short

The AIC device (Gay & Rabbia 1996) has been already used as a coronagraph on a single aperture for purpose of "on the sky" testing at the 3.6 m CFHT in Hawaii (Baudoz *et al.* 2000a, 2000b). Basically AIC is a Michelson-Fourier modified by adding a focus in one arm (see figures below). The achromatic π phase shift is provided by the focus-crossing property (Gouy 1890), yielding an intrinsically achromatic π phase shift. This latter is performed by a parabolic cat's eye system in one arm whilst flat mirrors are inserted in the other arm to equalize optical paths in each arm. Used as an imaging device AIC provides two twin-images of a companion. Because of AIC has two outputs, one destructive, the other constructive, the overall transmission for each image is 0.25. Two constraints must be satisfied to efficiently operate AIC. First, the Optical Path Differences at recombination must be zero with an accuracy of a fraction of wavelength. Second, the pupilla complex transmission must be centro-symmetric (what includes the phase over the pupilla).

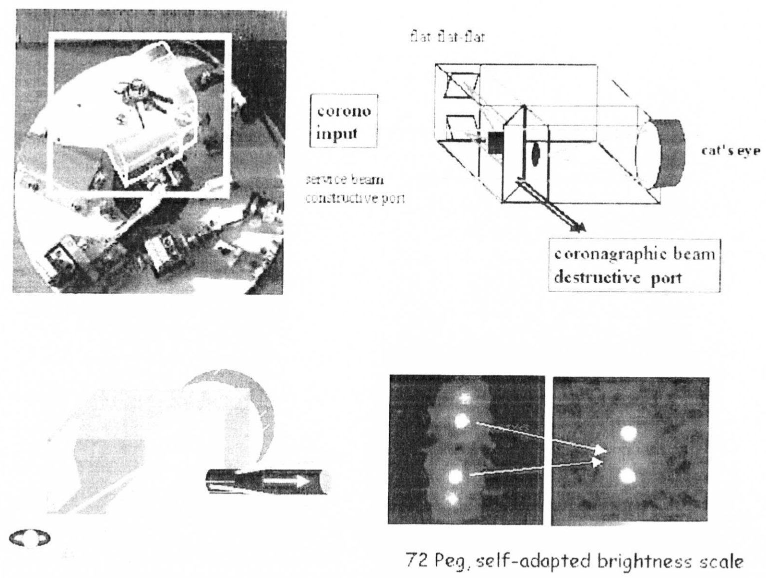

Fig. 3. Upper group, *left*: the AIC mounted on its optical interface for use on the 3.6 m CFHT, Hawaii. Upper group, *right*: travelling paths within AIC (beams travel in air, except for crossing the beamsplitter cube). Bottom group, *left*: AIC used as a coronagraph with a star on-axis and an off-axis companion. Bottom group, *right*: coronagraphic imaging with binary 72 Peg, the main component disappears when set on-axis, whilst twin-images of companions remain.

Beside using it as a coronagraph, AIC can be used in NI as both an Achromatic Phase Shifter and a Recombiner in a unique component, (see Fig. 4).

When the overall ($\phi 2 - \phi 1$) phase shift must be $\pi/2$, AIC can do it directly, provided that cylindrical optics are used instead of spherical ones (Rabbia et al. 2002b).

3.2 Using AIC as a Nuller

For Nulling Interferometry, the two constraints to satisfy with AIC require that piston between apertures and tilt over each aperture must be controlled and cancelled, to maintain a phased input-pupilla. This is actually needed with any nuller. Given these conditions, AIC works simply as a coronagraph looking at a diluted pupilla (instead of a compact one). Thus, a N-apertures interferometer pupilla can be accomodated by an AIC-nuller, and this applies to a densified output pupilla. The two-aperture case is described in Figure 4.

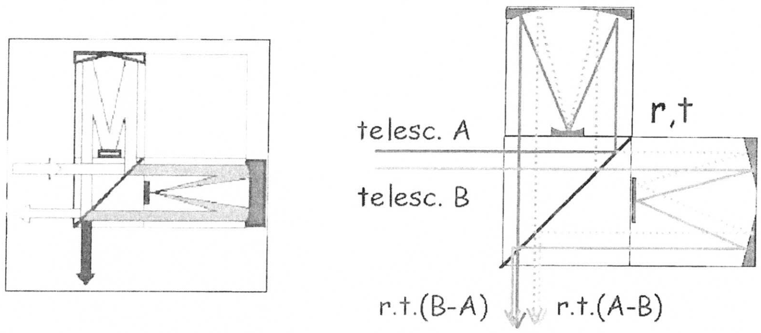

Fig. 4. *Left*: usual beam paths for coronagraphy with a single aperture. *Right*: beams management for AIC used in two-aperture Nulling Interferometry. Parameters r and t are beamsplitter coefficients for amplitude reflection and transmission respectively.

With A and B for the amplitudes from the on-axis star, collected by the telescopes, the beamsplitter at entry of AIC provides $r.A$ and $r.B$ by reflection and $t.A$ and $t.B$ by transmission. Beams from respective telescopes enter parallel into AIC which gives two nulled signals. Their respective amplitudes are described by $r.t.(A - B)$ and $r.t.(B - A)$. Their sum, performed by mixing them either in a fringe mode or in a flat-tint mode, yields the final nulled signal. Besides, photons from the star are driven to the constructive output. A point to emphasize pertains to the photons from the companion. When using AIC simply as an imaging-coronagraph (as mentioned above) the transmission for a single image of the companion is rather poor. This is not the case when AIC is used as a nuller, where the photons from the companion are fully recovered.

Let's have the baseline properly adjusted, which means that the first "right fringe" of the projected pattern is placed on the companion. Then, amplitudes from the companion bear a π-phase shift with respect to the amplitudes from the star. Thus, the amplitudes from the companion at the star-nulled output are $r.t.(a+b)$ and $r.t.(b+a)$, with "a" and "b" for the amplitudes collected from the companion. In other words, while the star amplitudes are nulled the companion's amplitudes are fully transmitted. The constructive output only conveys star's photons. Let's note that this output might be used for various controls, for example for a fine pointing servo-process.

Another point is to be emphasized which pertains to the coefficients "r" and "t". A recombining device using a beamsplitter in order to work on a large spectral domain (for example an atmospheric photometric window) meets the double problem of achieving a well-balanced (nearly 50/50) and achromatic energy splitting. Such a goal remains a much demanding technical challenge. Using AIC, since "r" and "t" works together in the product $r.t$, such problems are cancelled.

An extension to the 4-aperture case is possible using two cascaded AIC (Escarrat 2003) leading to 4 nulled outputs, which with an appropriate optical design, eventually provide the nulled signal for on-axis source and the total recovery of photons from a star's companion.

4 Conclusion

Among the various schemes that could be devised to perform a π (or $\pi/2$) achromatic phase shift between two collected waves and their recombination as well, the use of an AIC is worth considering, since it provides the two fonctions in a single compact optical device. Moreover, by contrast with the conventional use of AIC (imager in coronagraphic mode on a single aperture) AIC used as a nuller is able to fully recover photons from the companion.

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