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Optimisation of the SPHERE Adaptive Optics Setup at ~11 mag

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We have extended the recent analysis of the SPHERE adaptive optics (AO) performance for faint stars. In particular, we compared the raw contrast reached using the medium-frequency (600 Hz) and low-frequency (300 Hz) modes on different targets with G > 11 mag, and under different atmospheric conditions. We found that using the medium-frequency mode in this magnitude range leads to significantly better contrast. Based on these results, we have updated the AO frequency setup accordingly, that is, we extended the 600 Hz mode by one magnitude, up to 11.5 mag.

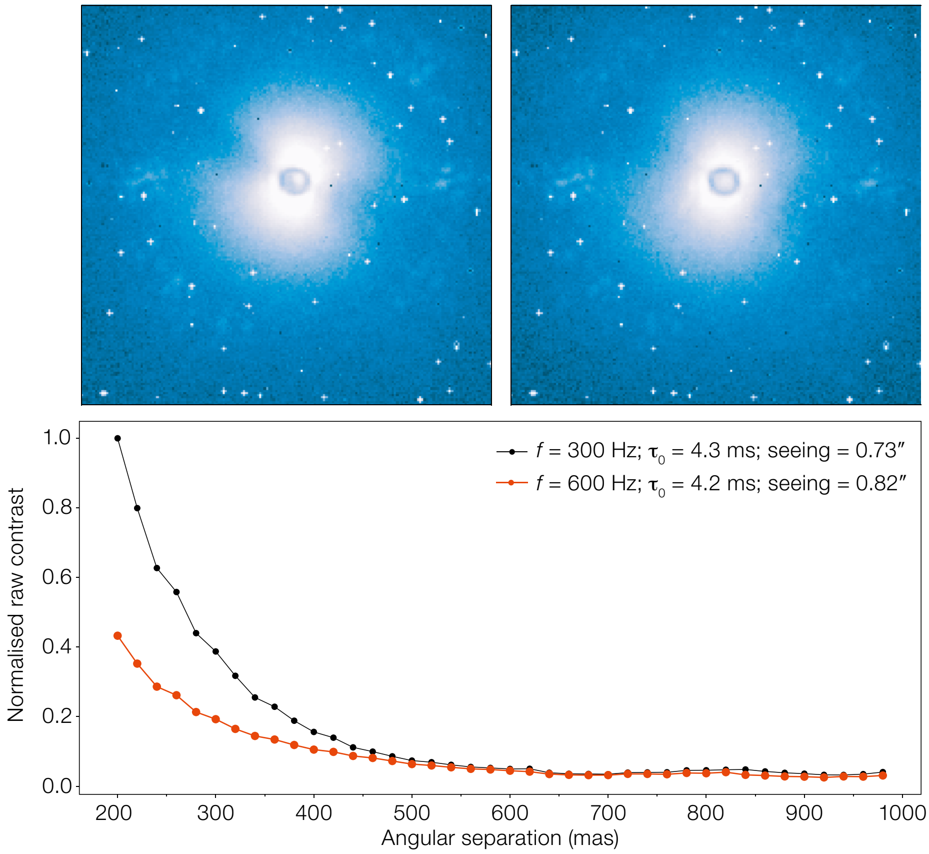

Figure 1. IRDIS coronagraphic raw images of V* NN Lup observed on 2023-06-16, using the 300 Hz and the 600 Hz modes (upper left and right image, respectively). The corresponding normalised raw contrast curves are shown below.

Introduction

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE; Beuzit et al., 2019) is a high-contrast imaging facility that is equipped with a powerful adaptive optics (AO) system, called SAXO (Fusco et al., 2006). The instrument comprises three different subsystems: the Zurich imaging polarimeter (ZIMPOL), which is sensitive to visible light; the InfraRed Dual-band Imager and Spectrograph (IRDIS) and the integral field spectrograph (IFS), that are sensitive to near-IR light (*Y*, *J*, *H* and *K* bands); and SAXO, which is equipped with a visible wavefront sensor (WFS). SPHERE has proven to be efficient at detecting faint companions and protoplanetary discs, reaching a final contrast better than 15 mag (beyond ~ 300 mas), when using angular and reference differential imaging (for example, Wahhaj et al., 2021) on bright targets, and reaching a Strehl ratio greater than 90%. However, one of the main limitations of SAXO is the use of a visible WFS, whose performance is strongly degraded beyond *G* ~ 12 mag, as shown by Jones et al. (2022; hereinafter J22). This limits our ability to study stars in young stellar associations, which are intrinsically red and hence significantly fainter in the visible than in the near-IR. This problem will be addressed by the SPHERE AO system upgrade, called SPHERE+ (Bocaletti et al., 2020), which will be equipped with a pyramid WFS sensitive to IR light. Hence, before this upcoming upgrade (whose first light is foreseen for 2027), it is very important to optimise the AO setup, so that we are able to reach the best possible AO correction, pushing the SAXO limits. Motivated by this, and based on the results presented in J22, we tested different setups to optimise the AO correction and to maximise the scientific return of SPHERE data.

Observations

We observed three stars on four different nights, under different atmospheric conditions[a]. Details of the observations are summarised in Table 1. We mainly followed the methodology presented in J22, that

Table 1. List of the observed stars, Gaia EDR3 *G*-band magnitude, night of observations, and mean atmospheric conditions during the observing sequence.

			300 Hz		600 Hz	
Star name	G mag	Night	τ_0 (ms)	seeing (arcsec)	τ_0 (ms)	seeing (arcsec)
V* NN Lup	11.6	2022-08-01	4.8	0.8	4.8	0.9
V* NN Lup	11.6	2023-06-16	4.4	0.5	4.5	0.5
UCAC2 18885095	11.3	2024-04-20	4.5	0.6	5.5	0.7
2MASS J13015435-4249422	11.1	2022-0731	4.5	0.8	4.7	0.8

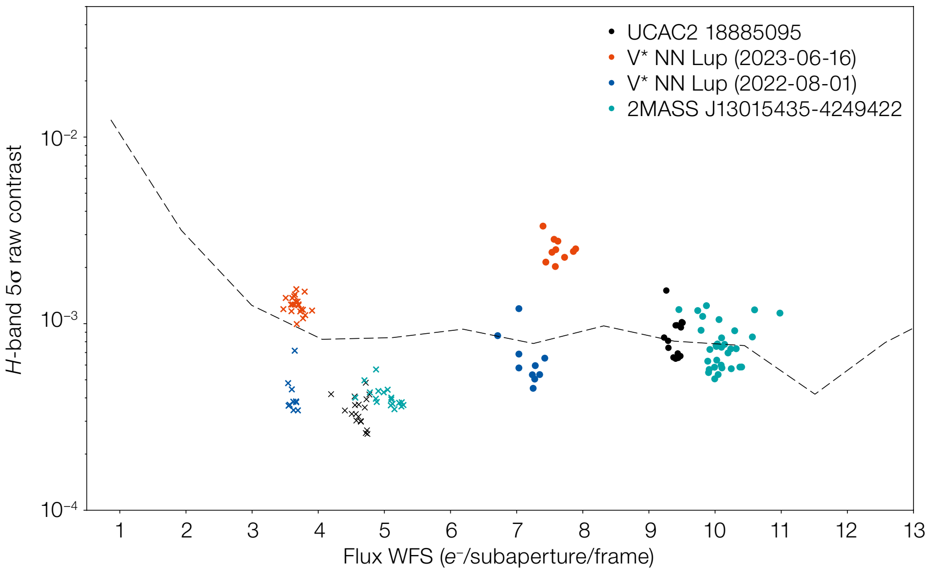

Figure 2. *H*-band raw contrast as a function of the instant flux received in the visible WFS. The dots and crosses correspond to individual frames observed with the 300 Hz and 600 Hz modes, respectively. The dashed line corresponds to the measured contrast for the 300 Hz mode, including observations taken under TCAT30 (τ_0 > 4.5 ms; seeing < 0.80 arcsec) or better atmospheric conditions (updated from Figure 3 in J22).

is, the observations were performed with IRDIS, using the H23 filter. For each star we first obtained a flux (F) sequence followed by an object (O) coronagraphic sequence. The detector integration time for each flux frame was between the minimum of 0.8 s and 8 s, and for the object frames was 32 s. We repeated the procedure using the same star, but this time changing between the low-frequency (f = 300 Hz) and the medium-frequency (f = 600 Hz) AO modes. We did this immediately after the first F–O sequence was finished, so that the airmass and atmospheric conditions were as close as possible between the two sets of observations.

Methods and results

For each individual frame in each sequence, we computed the normalised raw contrast curve, and the 5-σ raw contrast at a separation of 300 mas (see equation 1 of J22). To visualise the difference in the AO correction using these two modes, we compared individual frames and their resulting contrast curves. Figure 1 shows an example of this, for the *G* = 11.6 mag star V* NN Lup. The data were collected on 2023-06-16, under relatively good atmospheric conditions. The difference in the AO correction between the two different AO modes can be seen in the raw images. In particular, the effect of the wind-driven halo (see Cantalloube et al., 2020) is partially supressed with the 600 Hz mode. Moreover, the contrast curves show a significant improvement with this mode, up to a separation of about 500 mas. Finally, Figure 2 shows the raw contrast at 300 mas, as a function of the instant flux measured by the visible WFS, for the two different modes. As can be seen, there is a significant improvement (typically a factor of around two to three) in the raw contrast achieved when using the 600 Hz mode.

Summary and conclusions

Motivated by the results reported in J22, we have compared the SPHERE/IRDIS *H*-band raw contrast achieved when using the 300 Hz and 600 Hz AO frequency modes, for stars with *G* ~ 11 mag. For this, we performed back-to-back observations of stars in this magnitude regime, swapping between these two modes. As expected, we observed a significant improvement in the raw contrast when using the 600 Hz mode, in all four observing sequences. Based on these results, we adapted the SAXO AO setup table in August 2024, meaning that currently the faster correction mode is automatically selected up to *G* = 11.5 mag (in the past the limit was 10.5 mag). This was actually a relatively conservative choice, considering that we can expect a similar contrast for stars as faint as *G* ~ 12 mag, where the degradation of the AO correction is expected to take place (corresponding to about 3 e⁻ per subaperture per frame). We plan to re-adapt this limit accordingly. Finally, these tests show that for future instruments equipped with extreme AO systems, such as SPHERE+ itself, a more flexible AO frequency correction should be selected based on the instant flux on the WFS.

Acknowledgements

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Notes

[a] We excluded two stars from the analysis, since the atmospheric conditions were very unstable during the observing sequence.