LETTER TO THE EDITOR

Searching for Hα emitting sources around MWC 758 *

SPHERE/ZIMPOL high-contrast imaging

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ABSTRACT

Context. MWC 758 is a young star surrounded by a transitional disk. The disk shows an inner cavity and spiral arms that could be caused by the presence of protoplanets. Recently, a protoplanet candidate has been detected around MWC 758 through high-resolution L'-band observations. The candidate is located inside the disk cavity at a separation of ~111 mas from the central star, and at an average position angle of ~165.5°.

Aims. We aim at detecting accreting protoplanet candidates within the disk of MWC 758 through spectral angular differential imaging observations in the optical regime. In particular, we explore the emission at the position of the detected planet candidate.

Methods. We have performed simultaneous adaptive optics observations in the Hα line and the adjacent continuum using SPHERE/ZIMPOL at the Very Large Telescope (VLT).

Results. The data analysis does not reveal any Hα signal around the target. The derived contrast curve in the B, Ha filter allows us to derive a 5σ upper limit of ~7.6 mag at 111 mas, the separation of the previously detected planet candidate. This contrast translates into a Hα line luminosity of Lα < 5×10−5 L⊙ at 111 mas. Assuming that LHa scales with Lνc as in Classical T Tauri stars as a first approximation, we can estimate an accretion luminosity of Lacc < 3.7×10−4 L⊙ for the protoplanet candidate. For the predicted mass range of MWC 758b, 0.5-5 M⊕, this implies accretion rates smaller than ˙M < 3.4×10−8 M⊙/yr, for an average planet radius of 1.1 R⊕. Therefore, our estimates are consistent with the predictions of accreting circumplanetary accretion models for Rm = 1R⊕. The ZIMPOL line luminosity is consistent with the Hα upper limit predicted by these models for truncation radii ≤ 3.2 RJup.

Conclusions. The non-detection of any Hα emitting source in the ZIMPOL images does not allow us to unveil the nature of the L' detected source. Either it is a protoplanet candidate or a disk asymmetry.

Key words. stars: pre-main sequence – stars: planetary systems – stars: individual: MWC 758 – accretion, accretion disks

1. Introduction

The study of transitional disks is an important tool to understand planet formation and evolution. High-angular-resolution observations of these disks at different wavelengths have revealed structures including spiral arms, warps, gaps and radial streams that might be related to on-going planet formation (e.g. Andrews et al. 2011; Mayama et al. 2012; Grady et al. 2013; Boccaletti et al. 2013; Pinilla et al. 2015; Pérez et al. 2016; Mendigutía et al. 2017; Pohl et al. 2017). Therefore, a great effort has been made to detect protoplanets still embedded in these disks (e.g. Huélamo et al. 2011; Kraus & Ireland 2012; Quanz et al. 2013; Biller et al. 2014; Close et al. 2014; Whelan et al. 2015; Sallum et al. 2015), since they can shed light on the planet formation mechanisms, the required physical conditions, and the physics of gas accretion to form the atmospheres of giant planets.

In this context, MWC 758 (HD 36112, HIP25793) is an interesting target to study planet formation. The object has a young (3±2 Myr, Meesus et al. 2012) Herbig Ae star. While the Hipparcos parallax provided a distance of 279±24 pc (van Leeuwen et al. 2007). Therefore, a great effort has been made...
2. Observations and data reduction

2.1. VLT/ZIMPOL

The SPHERE Open Time observations (096.C-0267.A) were obtained on December 30, 2015. The ZIMPOL instrument of SPHERE (Beuzit et al. 2008; Thalmann et al. 2008) was used in spectral and angular differential imaging modes (Marois et al. 2006; Racine et al. 1999). In addition to the pupil stabilized mode, ZIMPOL simultaneously imaged MWC 758 in two different filters: B_Ha ($\lambda = 655.6$ nm and $\Delta \lambda = 5.5$ nm) and Cnt_Ha ($\lambda = 644.9$ nm and $\Delta \lambda = 4.1$ nm). We obtained 190 individual exposures of 60 seconds each, resulting in a total exposure time of ~3 hours on-source (from 02:20 UT to 05:24 UT). The conditions were photometric until 03:39 (UT) when they turned into clear.

The observing conditions (monitored by the seeing and coherence time) were variable during the complete observing sequence. The seeing varied between 0"7 and 2"0, and the coherence time between 5 ms and 2 ms (see Fig 1) affecting the final Adaptive Optics (AO) correction of the ZIMPOL images. Figure 2 shows the maximum counts registered on the target (good proxy for the Strehl variation in photometric/clarity conditions) throughout the 190 individual images in the B_Ha filter (the same variations are observed in Cnt_Ha). The mean full-width at half-maximum (FWHM) measured in the individual images was ~9 pixels, that is, ~32 mas considering the pixel scale of 3.6 mas/pixel of the ZIMPOL detector.

The data reduction was performed using a customary pipeline developed by our team. As a first step, the data were bias-subtracted, flat-fielded, and bad-pixel corrected. Subsequently, the individual images were recentered using a simple Moffat function to estimate the centroid position as no coronagraph was used. For the point-spread function (PSF) subtraction, the individual filter datasets (B_Ha and Cnt_Ha) were considered separately to apply a standard Angular Differential Imaging (ADI) processing technique using classical and smart-ADI (cADI and sADI; Lafrenière et al. 2007; Chauvin et al. 2012) and principal component analysis (PCA) (Soummer et al. 2012). For the B_Ha-Cnt_Ha spectral and angular differential imaging processing, the individual Cnt_Ha images were first spatially rescaled to the B_Ha filter resolution, then flux-normalized considering the total flux ratio between B_Ha and Cnt_Ha within an aperture of $r = 10$ pixels, before finally applying the subtraction B_Ha-Cnt_Ha frame per frame to exploit the simultaneity of both observations. ADI processing in cADI, sADI and PCA was then applied to the resulting differential datacube.

The ADI detection limits were then estimated from a standard pixel-to-pixel noise map of each filter within a box of 5x5 pixels sliding from the star to the limit of the ZIMPOL field of view. The contrast curves at 5$r$ were then obtained using the pixel-to-pixel noise map divided by the ADI flux loss, and corrected from small number statistics following the prescription...
of Mawet et al. (2014) adapted to our 5σ confidence level at small angles with ZIMPOL. The same method was applied for the differential imaging dataset to illustrate the gain in speckle subtraction in the inner region below 200 mas.

Finally, and to consider the impact of variable atmospheric conditions, we analyzed three different datasets (see Figure 2): first, we worked with the whole observing sequence (190 images) which covers a field rotation of ~55 degrees; second, we selected the best AO-corrected images through the whole exposure (images 44 to 90, and 162 to 190, a total of 76 frames, covering 15 deg and 7 deg of field rotation, respectively) and, third, we kept the 47 images with the best AO correction in the first half of the observing sequence (images 44 to 90, ~15 deg of field rotation). We finally worked with the latest dataset (47 individual images) to achieve the best detection performances at close separations. The average Strehl ratio of this dataset is ~10%.

2.2. CAHA/CAFE spectroscopy

To complement the SPHERE/ZIMPOL observations, we performed high-resolution spectroscopy of MWC 758 with the CAFE spectrograph attached to the 2.2m telescope in the Calar Alto Observatory (Aceituno et al. 2013). CAFE is equipped with a 2’/4 diameter optical fibre, and provides high-resolution spectra (R ~ 63 000) over the 3900-9600Å spectral range.

We obtained a spectrum on the night of December 24 2015 under photometric conditions and with an average seeing of 0’7. The total exposure time was 600 seconds. The spectrum was reduced with a dedicated pipeline developed by the observatory and explained in Aceituno et al. (2013). The processing was as follows: the data were bias subtracted and flat-field corrected. We used thorium-argon (ThAr) exposures obtained after the science spectrum to wavelength-calibrate the data. The spectrum was flux-calibrated using the standard star HD19445, observed one hour before the science target with an airmass difference of ~0.2. We compared the calibrated spectrum with published photometry (Beskrovnaya et al. 1999), obtaining that the spectrum is ~1.2 times brighter (0.2 mag) in the R-band. Therefore, we estimate a precision in the flux calibration of ~20% in this band.

Figure 3 shows a portion of the calibrated CAFE spectrum containing the Hα line. We measure a line flux of 1.3 × 10^{-11} erg/s/cm^2. To correct for the stellar photospheric absorption, we first computed synthetic spectra using the codes atlas and synth (Kurucz 1993) fed with the models describing the stratification of the stellar atmospheres (Castelli & Kurucz 2003). Solar abundances were assumed. The synthetic spectrum was computed assuming Teff = 7750 K and log g = 4.0 as the starting point, following the result from Beskrovnaya et al. (1999). A value of v sin i = 50 km/s was adopted since it reproduces well the width of the photospheric line profile. The model is displayed as a red line in Figure 3. The estimated Hα line flux, corrected from the photospheric absorption, is 1.6 ± 0.3 × 10^{-11} erg/s/cm^2. Taking into account the reported visual extinction of AV = 0.16 mag (Meeus et al. 2012), we can correct the flux adopting a value of AR ~ 0.12 mag (Rieke & Lebofsky 1985), and estimate a line luminosity of ~0.013 L⊙ for a distance of 151 pc.

Assuming that the Herbig Be/Ae relationship between Hα luminosity and accretion luminosity derived by Fairlamb et al. (2017) holds, we estimate log (Lacc/L⊙) = (2.09 ± 0.06) + (1.00 ± 0.05) × log (LHα/L⊙). We derive Lacc = 1.6 ± 0.4 L⊙. Following Mendigutía et al. (2011), we estimate a mass accretion rate of ~ (7 ± 2) × 10^{-8} M⊙/yr, for a stellar mass of 1.4 ± 0.3 M⊙ and a stellar radius of 2 R⊙ (Boehler et al. 2017), already scaled to the GAIA distance.

Finally, we note that although the CAFE spectrum is not simultaneous to the SPHERE observations, it allows us to characterize the primary star and to double-check the calibration of our ZIMPOL data with close in-time observations.

3. Results and discussion

The SPHERE/ZIMPOL combined images of MWC 758 in the B_Ha and the Cnt_Ha filters, together with the differential B_Ha–Cnt_Ha image, are displayed in Figure 4. We show the results of combining the 47 best images. We have not detected any point-like source in any of the analyzed datasets. The 5σ contrast achieved in the two individual filters, and in the differential sequence, is displayed in Figure 5. We reach ~7.6 mag in the B_Ha and the Cnt_Ha filters at a separation of 111 mas, that is, where the protoplanet candidate by Reggiani et al. (2017) is detected.
The fact that we do not detect any companion in the individual filters and differential images does not allow us a direct estimation of its \( H \) flux. However, since the 47 images were observed under photometric conditions, we can convert the \( B_H \) contrast curve into fluxes by calibrating the counts \((cts)\) from the primary star. To this aim, we first performed aperture photometry of the central star in ten individual images (out of the 47), using a large aperture radius (320 pixel radius, \( \sim1 \) arcsec). We obtain a total of \( -6.5(\pm0.6)\times10^{6} \) \( cts \). The uncertainty includes a relative error of 10% associated to the channel splitting, and the background error estimation. We converted the integrated counts into fluxes using the zero-points (ZPs) derived by Schmid et al. (2017), and their Eq. (4):

\[
f = \frac{(cts/s) \cdot 10^{0.4(\alpha_{\text{mag}}l_{\text{zp}} + m_{\text{mode}})} \cdot c_{\text{zp}}}{L_{\odot}}
\]

Assuming that all the emission in the \( B_H \) filter comes from the \( H \) line, we can convert the counts per second adopting a zero-point \((c_{\text{zp}})\) of \( 7.2(\pm0.4)\times10^{-16} \) erg/(cm\(^2\) \( s \)), and an \( m_{\text{mode}} \) value of \( -0.23 \) mag to take into account the usage of the \( R \)-band dichroic (Schmid, private communication). For an average air-mass \((\alpha_{\text{air}})\) of 1.57 (for the 47 images), and a typical \( R \)-band atmospheric extinction value of \( k_1 \sim 0.08 \) (Patat et al. 2011), we obtained a B\(_H\) flux of \( \sim7.1(\pm0.8)\times10^{-11} \) erg/s/cm\(^2\) for the primary star. We note that the assumption that all the counts in the \( B_H \) filter come from the line, results in a line flux overestimation of a factor of \( \sim5 \) when compared with the line flux measured directly in the spectrum.

We used the total calibrated flux in \( B_H \), together with the contrast curve, to derive an upper limit \((5-\sigma)\) to the \( B_H \) flux at different separations form the central object. In particular, we estimated a flux \( <6.2\times10^{-14} \) erg/s/cm\(^2\) at 111 mas, the separation of the planet candidate. If we assume that all the flux comes from the line, and an extinction equal to that of the \( L_H \) line, we can convert the counts in the \( B_H \) filter into the line flux overestimation of a factor of \( \sim5 \) when compared with the line flux measured directly in the spectrum.

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\[10^{-5} \, M_{\text{Jup}}^2 \text{yr}^{-1} \text{for disk inner radii of } R_{\text{in}} = 1 - 4 \, R_{\text{Jup}}, \text{respectively (see their Fig. 6). Given the mass constraints, their data is compatible with a 0.5-5 \, M_{\text{Jup}} \text{protoplanet with an accretion rate of } \, 10^{-7} - 10^{-9} \, M_{\text{Jup}} \, \text{yr}^{-1}.\]

As a first approximation, and following previous work (Close et al. 2014; Sallum et al. 2015), we can estimate the accretion luminosity \(L_{\text{acc}}\) of MWC 758 b assuming that it scales with \(L_{\text{H}_\alpha}\) as in Classical T Tauri stars (CTTSs). In this case, \(L_{\text{acc}} = 10^{-2.9(9+0.16) \times \log(L_{\text{H}_\alpha})}\) (Rigliaco et al. 2012), and we derive an upper limit of \(L_{\text{acc}} < 3.7 \times 10^{-4} \, L_{\odot}\) at 111 mas. Using the \(L_{\text{acc}}\) upper limit, and following Gullbring et al. (1998), we estimate \(M_{\text{Jup}} < 1.8 \times 10^{-5} \, M_{\text{Jup}}^2 \, \text{yr}^{-1}\), assuming a planet radius of 1.1 \(R_{\text{Jup}}\) (the average value for 0.5-5 \(M_{\text{Jup}}\) planets according to 3Myr COND models, Baraffe et al. 2003). This upper limit is consistent with the lowest values of \(M_{\text{J}} \, M_{\text{p}}\) derived for \(R_{\text{in}} = 1 \, R_{\text{Jup}}\) by Reggiani et al. (2017). If we assume planet masses of 0.5-5 \(M_{\text{Jup}}\) and a planet radius of 1.1 \(R_{\text{Jup}}\), we estimate accretion rates of \(M < 3.4 \times 10^{-8} - 9 \times 10^{-9} \, M_{\odot} \, \text{yr}^{-1}\) for MWC 758 b.

We note, however, that low-mass brown dwarfs and planetary mass objects seem not to follow the \(L_{\text{H}_\alpha} - L_{\text{acc}}\) relation derived for CTTSs: as an example, Zhou et al. (2014) estimated the accretion rates of three very low-mass substellar sources through their UV/optical eclipses, and found values more than one order of magnitude higher than the values expected from extrapolating the CTTSs relationship. Interestingly, they also show, in contrast with young TTs, very low-mass accreting objects might emit a larger fraction of their accretion luminosity in the \(\text{H}_\alpha\) line.

An alternative way to study the \(\text{H}_\alpha\) emission of protoplanets is to compare their estimated luminosity with predictions from accreting circumplanetary models (Zhu 2015). In this latter work, the author studied the expected \(\text{H}_\alpha\) emission from protoplanets due to magnetospheric accretion (see their Eq. 22), obtaining upper limits to their \(L_{\text{H}_\alpha} - L_{\text{acc}}\) luminosity three orders of magnitude higher than the typical values derived for CTTs \((<5 \times 10^{-13} \, L_{\odot})\), Rigliaco et al. (2012). The line luminosity depends on the truncation radius of the inner disk, and the infall velocity of the accreted material. According to their Eq. 22, our ZIMPOL data \((L_{\text{H}_\alpha} < 5 \times 10^{-9} \, L_{\odot})\) is consistent with their predicted luminosity for truncation radii smaller than \(3.2 \, R_{\text{Jup}}\).

The fact that we do not detect any source in the B-\(\text{H}_\alpha\) filter might suggest that the MWC 758 protoplanet candidate is accreting at a low rate and we are not sensitive to its \(\text{H}_\alpha\) emission. Another possibility is that the object is undergoing episodic accretion and we have observed it in a quiescent state. Although the disk inclination is closer to face-on, the \(\text{H}_\alpha\)-band is filled with small grains (Benisty et al. 2015), so the object might also be too extincted and therefore undetectable in the optical regime. Finally, we cannot exclude the possibility that the \(L_{\text{K}}\) infrared emission is related to a disk asymmetry and not with a protoplanet, as proposed by Reggiani et al. (2017). In fact, it is known that ADI techniques can highlight disk features in such a way that they can look like planets, especially for low-inclination systems (see e.g. Ligi et al. 2018). Follow-up \(L_{\text{K}}\) observations, together with deeper \(K\)-band data, will help to understand the true nature of the infrared detection.

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