

LETTER TO THE EDITOR

# Searching for H $\alpha$ emitting sources around MWC 758

## SPHERE/ZIMPOL high-contrast imaging<sup>★,★★</sup>

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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  $\sim 111$  mas from the central star, and at an average position angle of  $\sim 165.5^\circ$ .

**Aims.** We aim at detecting accreting protoplanet candidates within the disk of MWC 758 through angular spectral differential imaging (ASDI) 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 H $\alpha$  line and the adjacent continuum using SPHERE/ZIMPOL at the Very Large Telescope (VLT).

**Results.** The data analysis does not reveal any H $\alpha$  signal around the target. The derived contrast curve in the B $_H$  filter allows us to derive a  $5\sigma$  upper limit of  $\sim 7.6$  mag at 111 mas, the separation of the previously detected planet candidate. This contrast translates into a H $\alpha$  line luminosity of  $L_{H\alpha} \lesssim 5 \times 10^{-5} L_\odot$  at 111 mas. Assuming that  $L_{H\alpha}$  scales with  $L_{\text{acc}}$  as in classical T Tauri stars (CTTSs) as a first approximation, we can estimate an accretion luminosity of  $L_{\text{acc}} < 3.7 \times 10^{-4} L_\odot$  for the protoplanet candidate. For the predicted mass range of MWC 758b,  $0.5\text{--}5 M_{\text{Jup}}$ , this implies accretion rates smaller than  $\dot{M} < 3.4 \times (10^{-8}\text{--}10^{-9}) M_\odot \text{ yr}^{-1}$ , for an average planet radius of  $1.1 R_{\text{Jup}}$ . Therefore, our estimates are consistent with the predictions of accreting circumplanetary accretion models for  $R_{\text{in}} = 1 R_{\text{Jup}}$ . The ZIMPOL line luminosity is consistent with the H $\alpha$  upper limit predicted by these models for truncation radii  $\lesssim 3.2 R_{\text{Jup}}$ .

**Conclusions.** The non-detection of any H $\alpha$  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 – planetary systems – stars: individual: MWC758 – accretion, accretion disks – techniques: high angular resolution

## 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, 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 reduced images are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](http://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/613/L5>

\*\* Based on observations obtained at Paranal Observatory under program 096.C-0267(A) and 96.C-0248(A).

the physics of gas accretion to form the atmospheres of giant planets.

In this context, MWC 758 (HD 36112, HIP 25793) is an interesting target to study planet formation. The object is a young ( $3 \pm 2$  Myr, Meeus et al. 2012) Herbig Ae star. While the HIPPARCOS parallax provided a distance of  $279^{+94}_{-58}$  pc (van Leeuwen 2007), the *Gaia* TGAS Catalog reports a parallax of  $6.63 \pm 0.38$  mas, resulting in a distance of  $151^{+10}_{-8}$  pc (Gaia Collaboration 2016a,b).

MWC 758 is surrounded by a transitional disk spatially resolved at infrared (IR) and (sub)millimeter wavelengths (Chapillon et al. 2008; Isella et al. 2010; Andrews et al. 2011; Grady et al. 2013; Marino et al. 2015). The disk inclination is  $21 \pm 2^\circ$ , and it shows several structures and a marginally resolved cavity. Benisty et al. (2015) presented SPHERE/IRDIS IR polarimetric observations of the source in the *Y*-band ( $1.04 \mu\text{m}$ ). The unprecedented angular resolution of these observations allowed them to spatially resolve several non-axisymmetric features down to 26 au ( $\sim 14$  au with the new *Gaia* distance), and an incompletely depleted cavity. They also resolved the two spiral arms previously reported by Grady et al. (2013) through HiCIAO observations. They presented a model that concludes that the presence of planets inside the cavity cannot reproduce the large opening angle of the spirals. On the other hand, models with an outer companion could work better to explain these disk structures (see e.g., Dong et al. 2015). More recently, Boehler et al. (2018) presented new sub-millimeter ALMA data showing a large dust cavity of  $\sim 40$  au in radius, evidence of a warped inner disk, and the presence of two dust clumps in the outer regions of the disk. To explain the whole disk structure, they propose the presence of two giant planets, one in the inner regions responsible for carving the cavity, and an outer one responsible for the spirals.

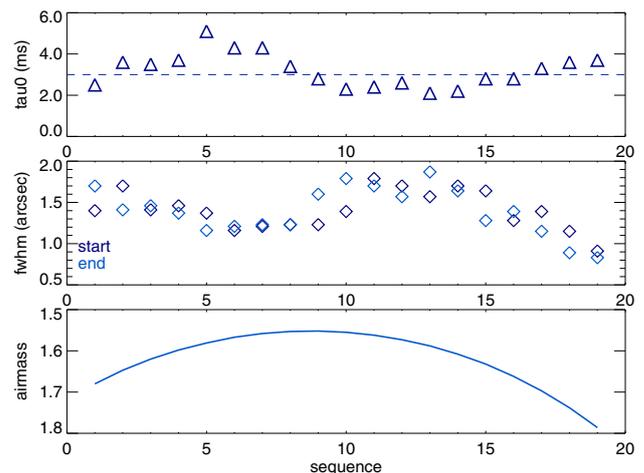
Interestingly, Reggiani et al. (2018) reported the presence of a point-like source inside the sub-millimeter cavity, at a separation of  $\sim 111 \pm 4$  mas from the central star. The object was detected in the *L*-band at two different epochs, with a contrast of  $\Delta L = 7.0 \pm 0.3$  mag with respect to the primary. As the authors explain, this emission could be caused by an embedded protoplanet, although they cannot exclude that it is associated with an asymmetric disk feature. The comparison of their observations with circumplanetary disk accretion models (Zhu 2015) are consistent with a  $0.5\text{--}5 M_{\text{Jup}}$  planet accreting at a rate of  $10^{-7}\text{--}10^{-9} M_{\odot} \text{yr}^{-1}$ .

We have explored the possibility of detecting protoplanet candidates using the  $H_{\alpha}$  emission line as an accretion tracer (see e.g., Close et al. 2014; Sallum et al. 2015). In this letter, we present spectral angular differential imaging observations of MWC 758 obtained with SPHERE/ZIMPOL at the Very Large Telescope (VLT). We used two filters, one centered at the  $H_{\alpha}$  line, and the other one at the adjacent continuum. We complemented the ZIMPOL data with optical spectroscopy using the CAFE spectrograph at the 2.2 m telescope in the Calar Alto observatory. MWC 758 was part of a program to detect young accreting protoplanets within the circumstellar disks of young stars.

## 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

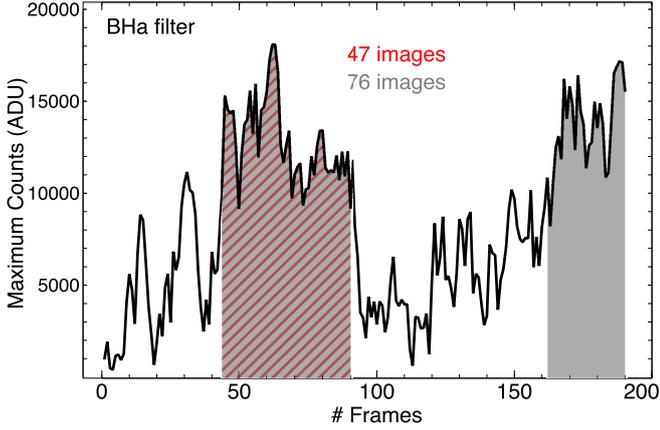


**Fig. 1.** Average atmospheric conditions during the ZIMPOL observations. The *x*-axis shows the average conditions in cycles of 10 min. Therefore, we have represented 19 cycles of 10 min each. From top to bottom, we have plotted the coherence time ( $\tau_0$ ), the average FWHM as seen by the guide probe at the beginning and end of the cycles, and the airmass.

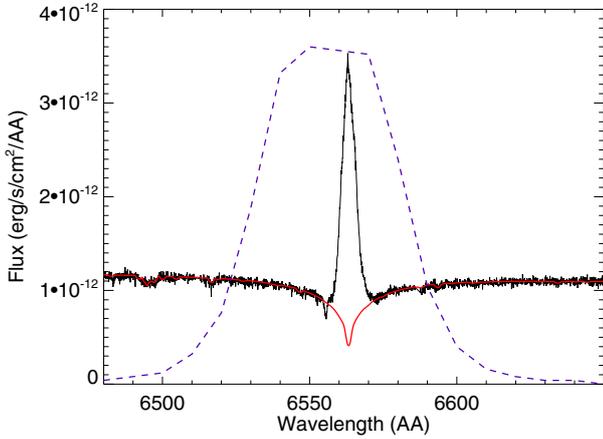
in spectral and angular differential imaging modes (Marois et al. 2006; Racine et al. 1999). In addition to the pupil stabilized mode, ZIMPOL simultaneously imaged MWC 758 in two different filters: B\_Ha ( $\lambda_c = 655.6$  nm and  $\Delta\lambda = 5.5$  nm) and Cnt\_Ha ( $\lambda_c = 644.9$  nm and  $\Delta\lambda = 4.1$  nm). We obtained 190 individual exposures of 60 seconds each, resulting in a total exposure time of  $\sim 3$  h 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/clear 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 is  $\sim 9$  pixels, that is,  $\sim 32$  mas considering the pixel scale of  $3.6 \text{ mas pixel}^{-1}$  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 (B\_Ha and Cnt\_Ha) datasets 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.



**Fig. 2.** Maximum counts (in ADU) measured in the 190 individual frames obtained in the B\_Ha filter. The gray shaded areas correspond to the 76 selected images (see text), while the hatched red area corresponds to the best 47 individual exposures.



**Fig. 3.** The observed CAFE/CAHA spectrum around the H $\alpha$  line (in black). The red line represents the model used to fit the stellar atmosphere (see text). The dashed blue line represents the ZIMPOL B\_Ha filter transmission curve.

The ADI detection limits were then estimated from a standard pixel-to-pixel noise map of each filter within a box of  $5 \times 5$  pixels sliding from the star to the limit of the ZIMPOL field of view. The contrast curves at  $5\sigma$  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  $5\sigma$  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 Fig. 2): first, we worked with the whole observing sequence (190 images) which covers a field rotation of  $\sim 55^\circ$ ; second, we selected the best AO-corrected images through the whole exposure (images 44–90, and 162–190, a total of 76 frames, covering  $15^\circ$  and  $7^\circ$  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 44–90,  $\sim 15^\circ$  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  $\sim 10\%$ .

## 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 2.2 m 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 ( $R \sim 63\,000$ ) over the 3900–9600 Å 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 s. 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 HD 19445, observed one hour before the science target with an airmass difference of  $\sim 0.2$ . We compared the calibrated spectrum with published photometry (Beskrovnaya et al. 1999), obtaining that the spectrum is  $\sim 1.2$  times brighter (0.2 mag) in the R-band. Therefore, we estimate a precision in the flux calibration of  $\sim 20\%$  in this band.

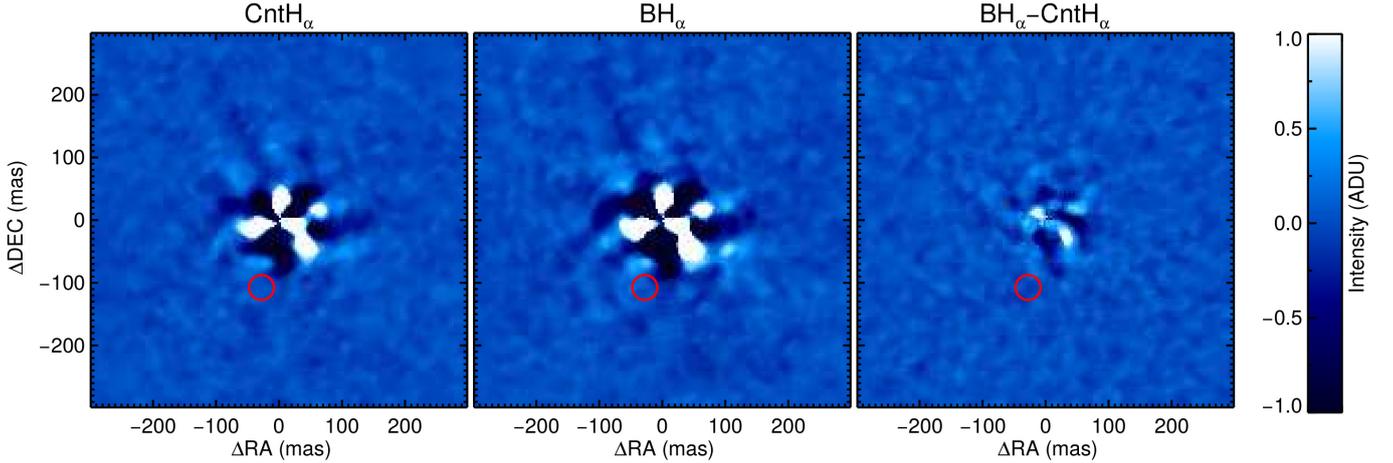
Figure 3 shows a portion of the calibrated CAFE spectrum containing the H $\alpha$  line. We measure a line flux of  $1.3 \pm 0.3 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$ . To correct for the stellar photospheric absorption, we first computed synthetic spectra using the codes ATLAS and SYNTHÉ (Kurucz 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  $T_{\text{eff}} = 7750$  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 $^{-1}$  was adopted since it reproduces well the width of the photospheric line profiles. The model is displayed as a red line in Fig. 3. The estimated H $\alpha$  line flux, corrected from the photospheric absorption, is  $1.6 \pm 0.3 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$ . Taking into account the reported visual extinction of  $A_V = 0.16$  mag (Meeus et al. 2012), we can correct the flux adopting a value of  $A_R \sim 0.12$  mag (Rieke & Lebofsky 1985), and estimate a line luminosity of  $\sim 0.013 L_\odot$  for a distance of 151 pc.

Assuming that the Herbig Be/Ae relationship between H $\alpha$  luminosity and accretion luminosity derived by Fairlamb et al. (2017) holds, we estimate  $\log(L_{\text{acc}}/L_\odot) = (2.09 \pm 0.06) + (1.00 \pm 0.05) \times \log(L_{\text{H}\alpha}/L_\odot)$ . We derive  $L_{\text{acc}} = 1.6 \pm 0.4 L_\odot$ . Following Mendigutía et al. (2011), we estimate a mass accretion rate of  $\sim (7 \pm 2) \times 10^{-8} M_\odot \text{ yr}^{-1}$ , for a stellar mass of  $1.4 \pm 0.3 M_\odot$  and a stellar radius of  $2 R_\odot$  (Boehler et al. 2018), already scaled to the Gaia distance.

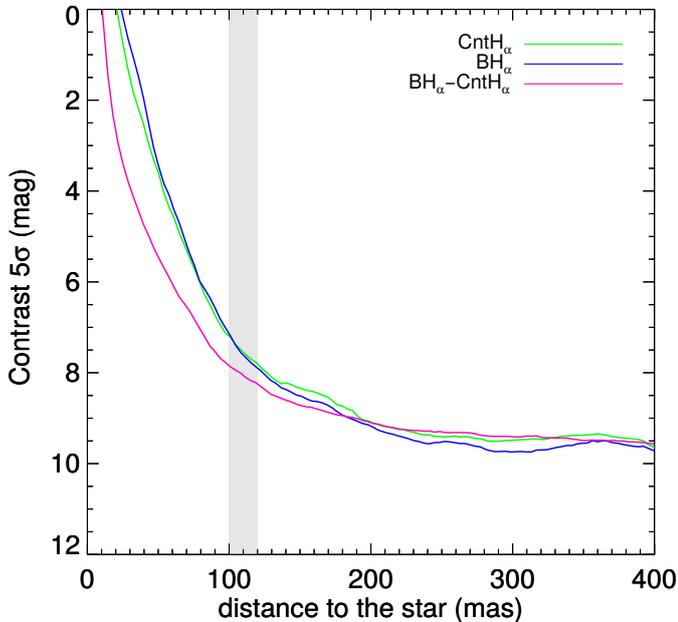
Finally, we note that although the CAFE spectrum is not simultaneous to the SPHERE observations, it allows us to characterize the primary star and to double-check the calibration of our ZIMPOL data with close in-time observations.

## 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 Fig. 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  $5\sigma$  contrast achieved in the two individual filters, and in the differential sequence, is displayed in Fig. 5. We reach  $\sim 7.6$  mag in the B\_Ha and the Cnt\_Ha filters at a separation of 111 mas, that



**Fig. 4.** VLT/ZIMPOL ADI reduced images of MWC 758 processed with PCA (5 modes) in the Cnt\_Ha (*left*) and B\_Ha (*center*) filters. The ASDI image (B\_Ha-Cnt\_Ha) processed with PCA (5 modes) is displayed in the *right panel*. North is up and East to the left. The red circle shows the position at a separation of 111 mas, and a PA of 165.5°, where the companion candidate was detected by [Reggiani et al. \(2018\)](#) in the  $L'$ -band.



**Fig. 5.** VLT/ZIMPOL  $5\sigma$  contrast curves obtained in Cnt\_Ha and B\_Ha in ADI using PCA, and in B\_Ha-Cnt\_Ha in ASDI using PCA. The gray area shows the position of the companion candidate detected at  $L'$  by [Reggiani et al. \(2018\)](#). The curves are derived using the best 47 images.

is, where the protoplanet candidate by [Reggiani et al. \(2018\)](#) 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  $H_\alpha$  flux. However, since the 47 images were observed under photometric conditions, we can convert the B\_Ha 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,  $\sim 1$  arcsec). We obtain a total of  $\sim 6.5(\pm 0.6) \times 10^6$  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):

$$f = (\text{cts s}^{-1}) \times 10^{0.4(a_m \times k_1 + m_{\text{mode}})} \cdot c_{zp}^l \quad (1)$$

Assuming that all the emission in the B\_Ha filter comes from the  $H_\alpha$  line, we can convert the counts per second adopting a zero-point ( $c_{zp}^l$ ) of  $7.2(\pm 0.4) \times 10^{-16}$  erg/( $\text{cm}^2$  ct), 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 airmass ( $a_m$ ) 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\_Ha flux of  $\sim 7.1(\pm 0.8) \times 10^{-11}$  erg  $\text{s}^{-1}$   $\text{cm}^{-2}$  for the primary star. We note that the assumption that all the counts in the B\_Ha filter come from the line results in a line flux over-estimation of a factor of  $\sim 5$  when compared with the line flux measured directly in the spectrum.

We used the total calibrated flux in B\_Ha, together with the contrast curve to derive an upper limit ( $5\sigma$ ) to the B\_Ha flux at different separations from the central object. In particular, we estimated a flux  $< 6.2 \times 10^{-14}$  erg  $\text{s}^{-1}$   $\text{cm}^{-2}$  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 primary star ( $A_R = 0.12$  mag), we estimate a line luminosity of  $L_{H_\alpha} < 4.9 \times 10^{-5} L_\odot$  for a distance of 151 pc. When compared with the other two  $H_\alpha$  sources detected in transitional disks, we see that our ZIMPOL upper limit is of the same order of the emission of the protoplanet candidate LkCa15 b ( $6 \times 10^{-5} L_\odot$ , [Sallum et al. 2015](#)), and one order of magnitude fainter than the very low-mass star ( $\sim 0.2 M_\odot$ ) HD142527 B ( $5 \times 10^{-4} L_\odot$ , [Close et al. 2014](#)). We note that the smallest and lightest accreting companions to stars in the brown dwarf/planet boundary (e.g., GQ Lup b, FW Tau b, GSC 06214–0210 b, DH Tau b) show  $H_\alpha$  luminosity values in the range  $L_{H_\alpha} \sim 2 \times 10^{-5} - 6.5 \times 10^{-7} L_\odot$  (see e.g., [Bowler et al. 2014](#); [Zhou et al. 2014](#)).

As explained in [Reggiani et al. \(2018\)](#), the mass of the companion candidate ( $M_p$ ) should be below  $5.5 M_{\text{Jup}}$  to allow for small dust replenishment within the disk. The comparison of their  $L'$ -band luminosity with circumplanetary accretion models ([Zhu 2015](#)) is consistent with  $M_p \dot{M} \sim 2(\pm 1) - 6.0(\pm 1.5) \times 10^{-5} M_{\text{Jup}}^2 \text{ yr}^{-1}$  for disk inner radii of  $R_{\text{in}} = 1 - 4 R_{\text{Jup}}$ , respectively (see their Fig. 6). Given the mass constraints, their data is compatible with a  $0.5 - 5 M_{\text{Jup}}$  protoplanet with an accretion rate of  $10^{-7} - 10^{-9} M_\odot \text{ yr}^{-1}$ .

As a first approximation, and following previous works (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  $L_{H_\alpha}$  as in classical T Tauri stars (CTTSs). In this case,  $L_{\text{acc}} = 10^{(2.99 \pm 0.16) + (1.49 \pm 0.05) \log(L_{H_\alpha})}$  (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  $M_p \dot{M} < 1.8 \times 10^{-5} M_{\text{Jup}}^2 \text{yr}^{-1}$ , assuming a planet radius of  $1.1 R_{\text{Jup}}$  (the average value for  $0.5\text{--}5 M_{\text{Jup}}$  planets according to 3 Myr COND models, Baraffe et al. 2003). This upper limit is consistent with the lowest values of  $M_p \dot{M}$  derived for  $R_{\text{in}} = 1 R_{\text{Jup}}$  by Reggiani et al. (2018). If we assume planet masses of  $0.5\text{--}5 M_{\text{Jup}}$  and a planet radius of  $1.1 R_{\text{Jup}}$ , we estimate accretion rates of  $\dot{M} < 3.4 \times (10^{-8}\text{--}10^{-9}) M_\odot \text{yr}^{-1}$  for MWC 758 b.

We note, however, that low-mass brown dwarfs and planetary mass objects seem not to follow the  $L_{H_\alpha}\text{--}L_{\text{acc}}$  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 excesses, and found values more than one order of magnitude higher than the values expected from extrapolating the CTTSs relationship. Interestingly, they also show that, in contrast with young TTSs, very low-mass accreting objects might emit a larger fraction of their accretion luminosity in the  $H_\alpha$  line.

An alternative way to study the  $H_\alpha$  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  $H_\alpha$  emission from protoplanets due to magnetospheric accretion (see their Eq. (22)), obtaining upper limits to their  $L_{H_\alpha}$  luminosity three orders of magnitude lower than the typical values derived for CTTSs ( $\sim 5 \times 10^{-3} L_\odot$ , 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 ( $L_{H_\alpha} \lesssim 5 \times 10^{-5} L_\odot$ ) is consistent with their predicted luminosity for truncation radii smaller than  $\sim 3.2 R_{\text{Jup}}$ .

The fact that we do not detect any source in the B\_Ha filter might suggest that the MWC 758 protoplanet candidate is accreting at a low rate and we are not sensitive to its  $H\alpha$  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 sub-millimeter cavity 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  $L'$  infrared emission is related to a disk asymmetry and not with a protoplanet, as proposed by Reggiani et al. (2018). 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  $L'$  observations, together with deeper  $K$ -band data, will help to understand the true nature of the infrared detection.

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