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EP Aquarii: A New Picture of the Circumstellar Envelope (Postprint)

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Abstract

A new analysis of early ALMA observations of the oxygen-rich AGB star EP Aquarii (EP Aqr) is presented here, which refines previously published studies and offers a different interpretation of the morpho-kinematics of the circumstellar envelope. The study shows that the formation of the equatorial density enhancement (EDE) occurs very close to the star, where evidence of rotation has been obtained. In regions close to the star where outflows have been observed, the interaction between the outflow and the nascent EDE gas plays an important role in the development of the stellar wind and the evolution of its radial velocity from 8-10 km s⁻¹ on the polar axis to approximately 2 km s⁻¹ at the equator. This implies that the morpho-kinematics are extremely complex, making it difficult to make reliable interpretations with reasonable confidence. In particular, the study questions an earlier interpretation that suggested the presence of a white dwarf companion at approximately 0.4 arcseconds from the stellar center. This paper instead proposes an explanation based on a standard mass ejection associated with a shock, which leaves behind an emission cavity. The high-velocity Doppler wings are confirmed to consist of two components: the velocity limit of the global stellar wind, reaching above ± 12 km s⁻¹; and effective line broadening, confined within 200 milliarcseconds of the stellar center and reaching above ± 20 km s⁻¹, which is interpreted as resulting from shock patterns generated by the interaction between stellar pulsation and the distribution of convective cells.

Full Text

Preamble

EP Aquarii: A New Picture of the Circumstellar Envelope

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Abstract

New analyses of earlier ALMA observations of the oxygen-rich AGB star EP Aquarii are presented, which complete a previously published analysis and offer a different interpretation of the morpho-kinematics of the circumstellar envelope. The birth of the equatorial density enhancement (EDE) is shown to occur very close to the star where evidence for rotation has been obtained. In this region, outflows interact with the gas of the nascent EDE and play an important role in the development of the wind and the evolution of its radial velocity from 8–10 km s⁻¹ on the polar symmetry axis to 2 km s⁻¹ at the equator. This implies complex morpho-kinematics that make reliable interpretations difficult. In particular, it questions an earlier interpretation implying the presence of a white dwarf companion orbiting the star at an angular distance of 0.4'' from its center. Instead, we propose an interpretation in terms of a standard mass ejection associated with a shock wave that leaves a void of emission in its wake. The high Doppler velocity wings are seen to consist of two components: the upper velocity end of the global wind, reaching above $\pm 12 \text{ km s}^{-1}$, and an effective line broadening confined within 200 mas from the center of the star, reaching above $\pm 20 \text{ km s}^{-1}$ and interpreted as caused by the pattern of shock waves resulting from the interaction between stellar pulsation and convective cell partition.

Key words: stars: AGB and post-AGB –(stars:) circumstellar matter –radio lines: stars

1. Introduction

When instruments providing high sensitivity and angular and spectral resolution became available—principally the Very Large Telescope (VLT) and the Atacama Large Millimeter/submillimeter Array (ALMA)—studies of the circumstellar envelopes (CSEs) of Asymptotic Giant Branch (AGB) stars progressed rapidly. Yet many questions remain unanswered concerning the mechanism that governs the generation and acceleration of the wind, particularly for oxygen-rich, low mass-loss rate stars. In contrast with carbon-rich stars, these have a dusty envelope that is more transparent in the visible and near-infrared (near-IR), giving

a better view of the innermost dust-forming atmospheric layers (Höfner & Freytag 2019). Their study supports a scenario where radiation pressure accelerates the outflows through photon scattering on highly transparent iron-free grains, such as corundum (Al_2O_3), which form a thin gravitationally bound dust layer close to the stellar photosphere. Beyond this layer, silicate dust condenses on top of corundum cores, speeding up grain growth to the critical size.

Recent high-resolution imaging of nearby AGB stars at visible and infrared wavelengths has revealed complex, non-spherical distributions of gas and dust in the close circumstellar environment, with changes in morphology and grain sizes occurring over weeks or months. At millimeter wavelengths, complexity is the main feature characterizing the morpho-kinematics of the CSE, with important anisotropy and inhomogeneity. Such distributions of atmospheric gas emerge naturally in 3D hydrodynamical models (Höfner & Freytag 2019) as a consequence of large-scale convective flows below the photosphere and the resulting network of atmospheric shock waves. The dynamical patterns in the gas are imprinted on the dust in the close stellar environment. Global AGB star models are characterized by giant convection cells that can span over a steradian and have lifetimes of many years. Together with radial pulsations (with typical periods of a few months), they generate waves of various frequencies and spatial scales that quickly develop into shock waves, giving rise to ballistic gas motions peaking around 2 stellar radii. As the shock waves interact and merge, they produce large-scale regions of enhanced densities in their wakes.

A consequence of this resulting complexity is the difficulty of reliably reconstructing the observed morpho-kinematics of the CSE in both velocity and space, driving its study to proceed somewhat by trial and error: successive observations and analyses bring new information that helps refine the picture. EP Aquarii (EP Aqr) provides such an example, with four recent publications by Homan et al. (2018), Hoai et al. (2019), Tuan-Anh et al. (2019), and Homan et al. (2020a). It is an M-type, semi-regular variable star (spectral type M8III) with a pulsation period of 110 ± 20 days (usually quoted as 55 days but more likely 110 days; Eggen 1973; Tabur et al. 2009), located at 119 ± 6 pc from the solar system (van Leeuwen 2007; Gaia Collaboration 2018). It shows no technetium in its spectrum (Lebzelter & Hron 1999) and has an effective temperature of 3240 K, a mass of 1.7 M_{\odot} , a radius of 0.77 au (Dumm & Schild 1998), and a mass-loss rate of $(1.6 \pm 0.4) \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Hoai et al. 2019).

The picture that emerges from these four recent studies of the CSE is two-component morpho-kinematics producing a Doppler velocity spectrum made of a narrow central peak at the star's systemic velocity and a broader plateau extending over $\pm 10-11 \text{ km s}^{-1}$. The central peak is associated with an oblate volume of gas, and the broad plateau with a prolate volume, both orbiting EP Aqr at a distance of $\sim 0.4''$ and currently located west of the star. The prolate volume of gas, usually referred to as the CSE, displays maximal velocity along the line of poles but clear density depressions near the poles, with

Evidence for rotation within some 100–200 mas from the center of the star, with rotation velocity at the km s^{-1} scale, has been obtained from observations of

CO(2-1), SO₂(42,2–31,3), and SO₂(166,10–175,13) line emissions (Homan et al. 2018; Tuan-Anh et al. 2019; Homan et al. 2020a). Observations of dust-induced polarization of the 550–750 nm emission at the VLT using SPHERE-ZIMPOL (Homan et al. 2020a) provide evidence for a shell of dust surrounding the star with an inner radius slightly smaller than 100 mas. A study of dust emission in the infrared using the Short Wavelength Spectrometer aboard the Infrared Space Observatory (ISO; Heras & Hony 2005) has revealed very low ratios of both gas-to-dust mass and aluminum oxide to silicates relative abundance.

No well-established interpretation of the observed morphology exists. EDEs are usually described as the result of gravitational attraction of the stellar wind in the orbital plane of a companion, and polar outflows are often interpreted as episodically produced by rapid rotation of an accretion disk surrounding this companion, reaching very high velocities. Such cases include HD 101584 (Olofsson et al. 2019) with highly collimated outflows reaching velocities of $\pm 140 \text{ km s}^{-1}$, π^1 Gruis (Doan et al. 2017; Homan et al. 2020b; Doan et al. 2020) with polar outflows consisting of thin hourglass-shaped bubbles reaching a radial expansion velocity of 60 km s^{-1} , V Hya (Sahai et al. 2022) with high-velocity lumpy jets of velocity 175 km s^{-1} , and R Aqr (Liimets et al. 2018; Melnikov et al. 2018; Bujarrabal et al. 2021) with outflows made of curved central jets with velocity reaching 240 km s^{-1} surrounded by hourglass bubbles in ballistic expansion with velocity of 55 km s^{-1} . Much closer to the morpho-kinematics of the EP Aqr CSE is that of AGB star RS Cnc, which however displays a clear technetium signal but is too far north to be observed by ALMA and has been studied in detail using NOEMA (Winters et al. 2022). It has two-component morpho-kinematics quantitatively similar to EP Aqr, with an axis making an angle of 30° with the line of sight and radial expansion velocities reaching $3\text{--}4 \text{ km s}^{-1}$ in the EDE and $8\text{--}9 \text{ km s}^{-1}$ in the bipolar outflows.

Neither EP Aqr nor RS Cnc has been shown to host a companion (though in both cases the presence of an undetected companion cannot be excluded), and no other known AGB star displays close enough morpho-kinematics to serve as a model for their CSE. The question of their genesis therefore remains open. In the case of EP Aqr, the picture proposed by Homan et al. (2020a)—suggesting the presence of an undetected white dwarf companion playing a major role in the formation and structure of the EDE—leaves several unanswered questions that call for further study:

- (i) High Doppler velocity wings reaching $\pm 20 \text{ km s}^{-1}$ were interpreted by Tuan-Anh et al. (2019) as two narrow polar structures, referred to as jets, launched from less than 25 au away from the star and building up between 20 and 100 au to maximal velocity. However, subsequent analyses of similar high Doppler velocity wings observed in several other stars (e.g., α Ceti; Hoai et al. 2020; Nhung et al. 2022) favored interpretations in terms of shocks produced close to the star by pulsations and convective cells, shedding strong doubts on the jet interpretation proposed for EP Aqr. It

has therefore become imperative to reconsider the case.

- (ii) The formation of the bipolar outflows remains unexplained. It may invite interpretations in terms of magnetic fields (García-Segura et al. 2005; Winters et al. 2022) or interacting winds in a binary system (Nordhaus & Blackman 2006; Castellanos-Ramírez et al. 2021), and more specifically in terms of an additional companion orbiting EP Aqr at a distance of 10 au (Homan et al. 2020a), but none of these can be solidly justified. The latter authors present several relevant suggestive arguments in relation to the observation of a complex pattern of arcs in the emission of the polar outflows.
- (iii) The formation of the EDE remains equally unexplained. The interpretation proposed by Homan et al. (2020a) in terms of focusing by an assumed white dwarf companion is in principle compelling but raises unanswered questions and likely faces inconsistencies when details of the observed morpho-kinematics are considered.
- (iv) A clear depression of SiO(5-4) line emission is observed in the western blueshifted octant and interpreted by Homan et al. (2020a) as the result of molecular dissociation produced by the ultraviolet (UV) radiation of the white dwarf companion. However, to the extent that the companion can be expected to sit in the median plane of the disk that it has generated, such dissociation should extend to the redshifted hemisphere as well, and the observed morphology of the depression is difficult to understand in such terms.

The aim of the present article is therefore to shed new light on these issues by presenting new additional analyses of the CO(2-1) and SiO(5-4) line emissions, particularly in the close neighborhood of the star. As a brief reminder of the main properties of the CSE of EP Aqr, we display in Figure 1 intensity maps of the CO(2-1) and SiO(5-4) line emissions, together with Doppler velocity spectra and a schematic description of the axi-symmetric geometry.

2. Observations and Data Reduction

We use archival ALMA observations of the CO(2-1) and SiO(5-4) line emissions of EP Aqr that were performed in 2016 and 2019 under projects ADS/JAO.ALMA#2016.1.00057.S and ADS/JAO.ALMA#2018.1.00750.S (PI: W. Homan). Observations and data reduction have been described in detail by Homan et al. (2018, 2020a) and need not be repeated here. The latter observations (referred to as TM0) used an extended antenna configuration and were combined with the earlier observations of lower angular resolution by Homan et al. (2020a) with a low weight of 20% due to concerns about possible artifacts associated with the lack of short spacings. In the present article, in order to better understand their contribution to the combined data, we

reduced them separately and report the results in this section. The combined data were obtained from Homan et al. (2020a) via the CDS (<http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/642/A93>). It should be sufficient to summarize their main features in Table 1.

The 2019 observations were made in two steps, on June 5 and June 14, with a hybrid antenna configuration (C43-10 and C43-9) including 46 antennas having baseline lengths between 83 and 16,000 m. A gap at short spacing (100-200 m), seen in the baseline length distribution of June 14 (Figure 2(a)), is due to the absence of four antennas (circled in red in Figure 2(b)). Four spectral windows were selected to observe line emissions of CO(2-1), SiO(5-4), SO₂(4_{2,2}-3_{1,3}), and ¹³CO(2-1). However, the latter two sets of data had insufficient sensitivity to contribute significantly new information and their analysis is omitted from the present work.

The data from the June 5 and 14 observations of the CO(2-1) and SiO(5-4) line emissions have been merged with equal weights and grouped in frequency channels corresponding to Doppler velocity intervals of 0.95 and 0.34 km s⁻¹, respectively. Natural weighting was used for cleaning, producing maps of 2000 × 2000 pixels covering ±4 in both x (pointing east) and y (pointing north), with full width at half maximum (FWHM) beam sizes of 31.7 × 28.0 mas² and 32.4 × 30.0 mas², respectively. We did not subtract the continuum contribution at visibility level, which would have been improper when looking over the stellar disk because of important absorption. We performed self-calibration, but as it did not result in significant improvement of the quality of the line images, the data used here do not include self-calibration.

The impact of the lack of short spacing below 100 m was found to differ between the CO(2-1) line, with emission extending up to some 10 angular distance from the star, and SiO(5-4) line emission, confined within some 3. Moreover, in the case of CO(2-1) line emission, it was also observed to be stronger near systemic Doppler velocity, where the emission is dominated by a disk extending to large angular distances. The size of the mask, which defines the region in the source plane over which the cleaning procedure is applied, must therefore be chosen accordingly. We studied images obtained with different mask sizes and retained a radius of 2 for the SiO(5-4) data and 1 for the CO(2-1) data, resulting in noise levels of 1.34 mJy beam⁻¹ for SiO(5-4) line emission and 1.0 mJy beam⁻¹ for CO(2-1) line emission.

While the nominal maximal recoverable scale (MRS) corresponding to the C43-10 antenna configuration is 0.46, the impact on imaging of the lack of short spacing cannot be simply measured by a single number. As the angular distance from the star increases, it reduces the detected flux first uniformly, then introduces anisotropic distortions of the emission pattern. We studied this effect in detail, both by comparing the produced images with those given by the combined data and by modeling the source as disks of various sizes. While the decline of detected flux starts well below the nominal MRS, important distortions appear only beyond 0.6-0.7. For the purpose of the present work, we

carefully checked that whenever TM0 data were used, proper account was taken of this issue.

Channel maps of the SiO(5-4) and CO(2-1) line emissions are shown in Figures S1 and S2 of the supplementary material. Examples of comparisons between TM0 and combined data are illustrated in Figures 2, 4, 14, and 15. We use Cartesian coordinates with the z-axis pointing away from Earth in addition to the x- and y-axes in the plane of the sky. We refer the Doppler velocity V_z to a systemic star velocity of -33.6 km s^{-1} in conformity with earlier work, though its value is not known to better than a fraction of a km s^{-1} . We define an angular distance from the center of the star as $R = \sqrt{x^2 + y^2}$ and a position angle ω measured counter-clockwise from north.

3.1. CO(2-1) Emission

Evidence for the presence of an EDE is known from previous work to rest exclusively on observations of the CO(2-1) and CO(1-0) line emissions (Hoai et al. 2019). However, a clear distinction between EDE and polar outflows could only be made at distances from the star exceeding $2 \text{ } \mu\text{m}$. The availability of high angular resolution data now makes it possible to study the EDE morphology at short distances from the star. As illustrated in the upper panels of Figure 3, Doppler velocity spectra integrated over successive rings centered on the star give clear evidence for the presence of the narrow component when R exceeds 200 mas , covering Doppler velocities between 0 and $+2 \text{ km s}^{-1}$. Remarkably, the neighboring channels between -3 and 0 km s^{-1} and between 2 and 5 km s^{-1} are depopulated. This may suggest that very close to the star, gas is bent toward the equatorial plane, depopulating these channels to the benefit of the narrow component. Channel maps integrated over the corresponding intervals of Doppler velocity are displayed in the lower panels of Figure 3. In the blueshifted depopulated Doppler velocity intervals, emission is enhanced in the northeastern quadrant. The intervals of high $|V_z|$ values (-10 to -3 and 5 to 12 km s^{-1}) host outflows expanding along the polar axes; these are discussed in Section 4.

To better explore the morpho-kinematics of the nascent EDE, we display in Figure 4 V_z versus ω maps of the CO(2-1) emission in 100 mas wide rings centered on the star. They show that the EDE is already present in the smaller ring with R between 100 and 200 mas , and its kinematics is dominated by rotation at a few km s^{-1} scale. This evidence for very early formation of the EDE had not been made explicit earlier, although Homan et al. (2020a) remarked that it is suggested by their SPHERE data. In particular, it raises questions in the context of the interpretation given by Homan et al. (2020a), which would imply an inner EDE radius of 400 mas corresponding to the orbit of the assumed companion, with strong anisotropy. Unfortunately, with presently available data, it is difficult to distinguish, in the immediate neighborhood of the star (say below $R = 200 \text{ mas}$), the contributions of expansion, rotation, and phenomena related

to the generation of the nascent wind: dust formation and shock waves caused by the interaction between stellar pulsation and convective cell partition (see Section 5).

Farther from the star, the EDE is seen to persist up to large distances, as illustrated in the left panels of Figure 5 by the PV maps of the line emission in the ring $1.2 < R < 5.2$ (see also channel maps of CO(2-1) emission shown in the Appendix in both the x versus y plane, Figure A1, and the ω versus R plane, Figure A2). These maps, drawn in the V_z versus R and V_z versus ω planes, show enhanced emission over all values of R and ω in the central Doppler velocity interval $|V_z| < 2 \text{ km s}^{-1}$. Similar PV maps in small intervals of ω and R are shown in the Appendix (Figures A3 and A4). In each (ω, R) bin with a width of $10^\circ \times 100 \text{ mas}$, we calculate the mean and rms values of V_z over the central Doppler velocity interval $|V_z| < 2 \text{ km s}^{-1}$. Their values are shown as a function of R and ω in the right panels of Figure 5, displaying remarkable uniformity: the rms value stays near 1 km s^{-1} over the whole radial range and the mean value near zero. A small ω asymmetry of the latter below $R = 3$ reveals an inclination of the EDE with respect to the plane of the sky consistent with the known inclination of the axis of the CSE with respect to the line of sight: it reaches values of 0.3 km s^{-1} in the northwestern direction and -0.3 km s^{-1} in the southeastern direction. This suggests a radial expansion velocity at the scale of $0.3/\sin 10^\circ = 1.7 \text{ km s}^{-1}$, consistent with the low value of 1.9 km s^{-1} retained in earlier studies (Hoai et al. 2019). The rms deviation of 1 km s^{-1} combines the effect of the known flaring angle of 15° ($\sin 15^\circ \times 1.7 = 0.44 \text{ km s}^{-1}$) with an intrinsic width of 0.9 km s^{-1} .

3.2. SiO(5-4) Emission

To compare CO(2-1) and SiO(5-4) line emissions in the close neighborhood of the star, we display in Figure 6 (for SiO(5-4) TM0 data) the same distributions as shown in Figure 3 for CO(2-1). They reveal a very different picture than those of CO(2-1) emission. The spectra cover a broad range of Doppler velocities independently of the distance to the star, with no sign of change beyond 200 mas. The narrow component contributes only a very small enhancement. Absorption from the outer layer having reached terminal velocity at $8\text{--}10 \text{ km s}^{-1}$ is seen in all four spectra. In contrast with CO(2-1) emission, the brightness maps show little structure but reveal a strong depression of emission at 400 mas west from the center of the star. This depression has been abundantly studied and commented upon in the earlier literature; we report on its properties in Section 4, to which we defer possible interpretations. Here we simply remark that the different temperature response of the two lines can only have small effects. They differ essentially by the value of the energy E_{up} of the upper level: 16.60 K for CO(2-1) and 31.26 K for SiO(5-4). This quantity enters the expression of the emissivity as a factor $e^{-E_{\text{up}}/T}$, where T is the temperature. The ratio between CO(2-1) and SiO(5-4) line emissions of the values taken by this

factor for $T = 10, 20, 50,$ and >100 K is 4.3, 2.1, 1.3, and <1.2 , respectively.

3.3. Patterns of Enhanced CO(2-1) Emission

The emission of the CO(2-1) line is known from earlier work to display significant fluctuations. Hoai et al. (2019) remarked that both CO(1-0) and CO(2-1) emissions in the EDE display remarkably similar fluctuations at the level of $\pm 36\%$, dominated by an eastern enhancement in the form of an arc and a southwestern depression, together having the appearance of a spiral. Homan et al. (2018) described similar data as evidence for a bright, nearly face-on spiral structure, claiming the first convincing detection of a spiral in the intensity fluctuations in the circumstellar environment of an oxygen-rich AGB star, with a higher degree of small-scale hydrodynamical structure and wider spiral arms than in carbon-rich environments. In their second paper, Homan et al. (2020a) gave a very detailed description of the EDE intensity fluctuations and concluded that the observed complex emission pattern strongly resembles typical hydrodynamical gas flow patterns associated with the interaction of a mass-losing AGB star with a companion. They claimed to have identified flow along the L1 and L3 Lagrange points before they coalesce into the spiral manifesting at larger length-scales, and argued for the presence of a companion located at 0.4 to the west of the star, probably a white dwarf with a mass between 0.65 and 0.8 M_{\odot} .

Channel maps of the combined CO(2-1) emission data in the twelve frequency channels that bracket the systemic velocity of the star ($-2.0 < V_z < 1.8$ km s $^{-1}$) are shown in Figure 7. They display arcs of enhanced emission, but the complexity of the patterns makes reliable interpretation in terms of well-identified individual components difficult. In particular, it makes it easy to interpret two partly overlapping arcs as a single one and an arc that is not centered on the star as a spiral arm. The human eye is too subjective a tool for reliable interpretation of the observed patterns. In this context, the reality of the spiral discovered by Homan et al. (2018) deserves critical discussion. There is no doubt that identifying such a spiral in the pair of central frequency channels (centered at 0.05 and -0.27 km s $^{-1}$, Figure 7) is natural and reasonable. However, we note that the neighboring channels (centered at 0.37 and -0.59 km s $^{-1}$, respectively) host patterns suggesting that the source of emission is in a plane inclined with respect to the sky plane: they shine in the northwestern direction for the redshifted side and in the southeastern direction for the blueshifted side, as expected for a plane perpendicular to the known axis of the CSE. Correcting for this tilt by averaging the brightness over the four central channels ($-0.75 < V_z < 0.53$ km s $^{-1}$), we obtain the map shown in the left panel of Figure 8. The identification of a spiral as proposed by Homan et al. (2018) and shown in the central panel of the figure is no longer obvious. Assessing the reliability of such spiral identification is indeed difficult. As illustrated in the right panel of Figure 8, arcs of spirals are excellent approximations to arcs of circles having their center offset with respect to the star's center. However, the two halves

of a single circle correspond to different spirals winding in opposite directions, whereas a proper spiral winds in a single direction and expands indefinitely; an arc having a point of closest approach to the star cannot be described as a single spiral.

In summary, the EDE is mostly seen in CO line emission as a disk slightly inclined with respect to the plane of the sky, formed within some 100 mas from the center of the star and having an rms flaring angle of 15° . Its small inclination prevents precise evaluation of the morpho-kinematics, but evidence has been obtained for rotation in the central region evolving to radial expansion at a low rate of less than 2 km s^{-1} beyond a fraction of an arcsec from the star. Such a small expansion velocity probably results in part from the low penetration of stellar radiation into the dense disk, limiting its effectiveness at accelerating dust grains. Assuming a 10 disk radius (Figure 6 of Homan et al. 2018), this implies that the disk is at least thirty centuries old. Arcs of enhanced emission are observed on the disk, but their interpretation as forming a spiral has been disputed.

4.1. CO(2-1) Emission

The polar outflows cover a broad region of the sky up to large velocities, as illustrated in Figure 9, which displays V_z versus R maps integrated over position angles for the blueshifted and redshifted hemispheres separately. A simplified schematic of the morpho-kinematics of the CSE is shown in the right panel of Figure 9. The polar outflows were observed earlier to display density fluctuations at the level of $\pm 26\%$ and projected angular distances from the star between 1.2 and 5.2 (Figures A1 to A4 of the Appendix). In some cases where one might fear that the steep radial decline of intensity would be a source of bias, we examined the brightness divided by a power-law fit to its radial distribution in the relevant frequency channel, found to have an index between -0.2 and -0.4 . In no case was this considered a source of significant bias.

Ideally, one would like to describe each channel map as a set of well-identified, separated arcs of enhanced emission. We attempted to do so using an algorithm lumping together brighter pixels, but failed to obtain a satisfactory result—the complexity of the patterns prevented reliable pattern recognition. Instead, for each frequency channel we carefully inspected the different projections of the data cube and tried to describe the observed patterns as simply and reliably as possible. Figure 10 displays a pair of representative examples; these have not been selected to show particularly clear patterns, as there are many examples of both clearer and more obscure cases.

Rather than giving a detailed review of our observations, we simply list the main statements we can make with confidence: in each map, the pattern of enhanced emission can be described as a set of arcs; they are too numerous and frequently overlapping to allow reliable pattern recognition; they can be approximated

by arcs of circles covering a few tens of degrees, typically less than 180° ; the contrast is small, with a peak-to-valley ratio not exceeding a factor of 2; the arcs always wind around the star, implying that the center of the associated circle is offset by less than a radius (typically half a radius) from the star's center; their radii cover a broad range of values, from as small as permitted by the angular resolution to as large as permitted by the size of the maps under study (from a fraction of an arcsecond up to over 5'); and very similar patterns are observed in adjacent frequency channels, covering ranges up to a few km s^{-1} . These comments complement usefully those made in this context by Homan et al. (2020a).

Finally, we remark that the V_z versus R map shown in Figure 5(b) (see also Figure A3 of the Appendix) provides precious information on the dependence of the radial expansion velocity on stellar latitude α . It was assumed to be of the form $V(\alpha) = V_{\text{eq}} + (V_{\text{pole}} - V_{\text{eq}})\sin^n\alpha$ in Hoai et al. (2019), where V_{eq} and V_{pole} are the expansion velocities at equator and pole, respectively. As illustrated in Figure 11, a small volume of gas at distance r from the star, at latitude α and having radial velocity V , has coordinates $(R, Vz) = (r \cos\alpha, V \sin\alpha)$. Namely, a spherical shell expanding at radial velocity V_0 and observed when it reaches radius R_0 is seen as a circle of unit radius in the PV map V_z/V_0 versus R/R_0 . In contrast, a ring expanding at the equator at velocity V_1 is seen as a point on the R axis at V_1/V_0 . Understanding the transition between the polar outflows and the EDE implies understanding the transition between these two regimes. A shell emitted at some time with velocity V_0 at the pole and velocity V_1 at the equator is seen as a curve of equation $V/V_0 = V_1/V_0 + (1 - V_1/V_0)f(\theta)$, where θ is the polar angle, with $f(0) = 0$ and $f(90^\circ) = 1$. However, θ equals the stellar latitude α because the reference radius R_0 used to define the axis of abscissa is the distance covered at velocity V_0 , used as reference velocity on the axis of ordinate. Thus the curve representing the shell in the PV diagram is a direct representation of the function $f(\alpha)$ that describes the dependence of stellar expansion velocity on latitude. The left panel of Figure 11 shows three examples of function $f(\alpha)$, all of the form $\sin^n\alpha$ with $n = 0.5, 1,$ and 2 respectively (in addition to the trivial cases $f(\alpha) = 0$ and 1). Comparison with low-latitude observations, as shown in the right panels of Figure 11 (see also Figure S3), clearly favors values of n smaller than 1, contradicting the arbitrary assumption made in Hoai et al. (2019). Specifically, it suggests that the outflows are close to portions of spherical shells when emitted at large stellar latitudes, and that their radial velocity decreases rapidly at small latitudes where their interaction with the disk becomes important. This is important information for modeling the hydrodynamical flow, though such modeling is beyond the scope of the present work.

Tentatively, the properties of the enhanced patterns of CO line emission in the polar outflows suggest they take the form of shells of episodic mass ejections and associated shock waves triggered by pulsations of amplitudes enhanced on the surface of convective cells. The confinement of such cells within solid angles at steradian scale limits the patterns observed in the channel maps to finite arcs

rather than full circles. Their radial velocity is maximal at the center of the cell and drops near its edges, causing the intersection of the shell with the sky plane of a given frequency channel to appear eccentric. Moreover, their mean radial velocity increases from the equator to the poles, implying a similar decrease in density and causing the polar depressions described by Hoai et al. (2019) and the “bi-conical outflows” appellation adopted by Homan et al. (2020a). Their patterns are best revealed when examining the V_z versus R distribution of line emission in a wedge of position angles not exceeding the size of the convective cell (as done in the right panels of Figure 11); integrating over the whole range of position angles or over a large radial distance smooths out the fluctuations resulting from the episodic nature of the mass ejections, which, as we shall see later, succeed each other at time intervals on the scale of a few decades. At the present stage, such an interpretation is highly speculative, but further observations described in the remainder of this section will confirm its likely validity.

4.2. SiO(5-4) Emission: General Features

In contrast to CO(2-1) emission, SiO(5-4) emission is confined within radial distances of $3''$, as shown in Figure 12, which displays radial distributions for both SiO(5-4) and CO(2-1) emissions. The emissions of the two lines are expected to differ in several respects: the SiO emission decreases with distance to the star, both because of condensation on dust grains and dissociation by UV interstellar radiation, and it is an efficient shock tracer.

As already remarked and clearly apparent in the distributions of SiO(5-4) emission displayed in Figure 13, one observes a significant asymmetry between the blueshifted and redshifted hemispheres. In particular, the former reveals a strong depression of emission at some 400-500 mas west of the star’s center that is challenging to interpret. We therefore limit our considerations to the morphokinematics of the red hemisphere. To illustrate the small inhomogeneity of the data cube, we show in Figure 13 the radial distribution $U(R)$, averaged over position angle and integrated over V_z , and the Doppler velocity spectrum $S(V_z)$ of the volume defined by $0.5'' < R < 2.3''$ and $0 < V_z < 8 \text{ km s}^{-1}$. We then compare the observed intensity to the product $U(R) \times S(V_z)$, properly normalized, in the right panels of the same figure. This reveals clearly the morpho-kinematics of the observed deviations with respect to a smooth distribution, though their amplitude is relatively modest (typically $\pm 20\%$). Both $U(R)$ and $S(V_z)$ show no significant fluctuation, and the lumps of enhanced emission have typical sizes on the scale of a fraction of an arcsecond. In contrast, on the V_z versus R and V_z versus ω maps, they cover several km s^{-1} .

Repeating the same analysis for the blueshifted hemisphere yields the result illustrated in the lower row of Figure 13. The main difference from the redshifted hemisphere is a lower intensity (33% reduction) dominated by an important

depression in the western quadrant, causing a deviation twice as large with respect to the smooth distribution. If not for this depression, both hemispheres would reveal similar morpho-kinematics that could be described by a simple, nearly spherical model, as previously remarked by Homan et al. (2020a). It is therefore important to study this depression in detail, which we do in the following subsection.

Channel maps of the SiO(5-4) line emission are shown as supplementary material (Figure S3). Also shown are PV maps in the V_z versus R plane (Figure S4) and in the V_z versus ω plane (Figure S5), which display episodic and lumpy emission.

4.3. SiO(5-4) Emission in the Close Neighborhood of the Star

Qualitatively, the upper and lower rows of Figure 13 display some similarities: below $R = 1$, both show enhanced emission in the polar outflows at $V_z = 7$ and -5 km s^{-1} , respectively, with the former covering the southern quadrant and the latter covering a broader interval of position angles, somewhat enhanced in the northeastern hemisphere. In contrast, beyond $R = 1$, emission is enhanced near the EDE.

Figure 14 displays V_z versus ω maps of SiO(5-4) emission in 100 mas wide rings centered on the star, in the same format as shown for CO(2-1) emission in Figure 4. Comparing the TM0 and combined data images and accounting for the different angular resolutions, they clearly reveal in the redshifted hemisphere an outflow covering the southern quadrant and a depression covering the northern quadrant. The picture is less clear in the blueshifted hemisphere, where enhanced emission covers velocity and position angle values closer to those displayed by the disk, while the western void shows up clearly in both TM0 and combined data images.

While qualitative similarities between both outflows and associated voids are remarkable, as clearly illustrated in Figure 15, important differences must be noted: (i) the western blueshifted depression of SiO(5-4) emission is stronger than the northern redshifted one, with a peak-to-valley ratio of 6 compared with 3; (ii) the northern SiO(5-4) depression starts earlier and is already present in the interval $0.1 < R < 0.2$, where the western depression is not only absent but even partly replaced by a clear enhancement; (iii) the southern outflow, covering large Doppler velocities, is emitted in the redshifted hemisphere close to the line of sight, while the blueshifted outflow, covering small Doppler velocities, is likely to interact with the nascent EDE in the equatorial plane. Indeed, Figure 16 shows that the CO(2-1) emission of the EDE displays a western void of emission clearly associated with the edge of the blueshifted void of SiO(5-4) emission, as previously remarked by Homan et al. (2020a). These observations underscore the complexity of the dynamics at stake and suggest that the interaction between the blueshifted outflow and the nascent EDE may play an important role.

Particularly puzzling are the properties displayed by the blueshifted western void of SiO(5-4) emission. To explore these in more detail, we take advantage of its confinement to a relatively narrow interval of position angle ($240^\circ < \omega < 300^\circ$) to study the distributions of the CO and SiO line emissions in the Vz versus R plane, integrated over ω . These are displayed in the left panels of Figure 17. Both give evidence for a mass ejection in the form of a shell having a mean radius between 0.5 and 1 and a mean radial velocity between 5 and 10 km s⁻¹. The void of emission for both SiO and CO lines is clearly seen in its wake, suggesting that it simply results from the radial velocity of the shell significantly exceeding that of the wind that followed it. As a distance of 1 is covered in the plane of the sky in 60 yr at a velocity of 10 km s⁻¹, the mass ejection occurred a few decades ago. We note that the distribution of the CO line emission suggests the presence of an earlier mass ejection that took place a few decades before the more recent one. It is not expected to be visible in the distribution of SiO line emission, as the density of SiO gas has significantly decreased at the corresponding radial distance. In line with the interpretation given at the end of Section 4.1 for the patterns observed in the CO line emission of the polar outflows, Figure 17 suggests the occurrence of mass ejections triggered by pulsations of amplitudes enhanced both episodically (with a timescale of a few decades) and in solid angle (at the scale of a steradian corresponding to the presence of a large convective cell). The angular resolution of the present observations cannot resolve the fine time structure associated with the pulsation period (110 days).

A significant difference between the distributions of SiO and CO line emissions displayed in Figure 17 is the evidence for SiO emission having resumed after the mass ejection, covering some 100-200 mas from the star's center, while CO emission has not. Indeed, we saw in Figure 3 that close to the star and in the Doppler velocity interval $-3 < Vz < 0$ km s⁻¹, CO line emission is instead enhanced in the northeastern quadrant. In contrast, we saw from Figure 6 that in the same region of the data cube, SiO emission covers the whole range of position angles. Understanding the reason for such a difference would require understanding the mechanism that governs the formation of the equatorial disk, which demands observations of higher sensitivity and of other line emissions, both of which are lacking. We note that the ejected shell covers latitudes reaching down to the disk, implying that it interacts with it, making it even more difficult to provide a reliable interpretation of the mechanism at stake.

To explore the properties of the northern depression, we repeated the analysis made for the western void in the interval of position angles $280^\circ < \omega < 360^\circ$. The result is illustrated in the right panels of Figure 17. Here again, in the range of large Doppler velocities ($Vz > 7$ km s⁻¹), the depression is seen in the wake of a shell-like enhancement of emission, much clearer in the CO distribution than in the SiO distribution, and an earlier shell is clearly visible in the CO distribution. Also, as for the western void, SiO line emission is seen to have resumed close to the star after the mass ejection, but CO line emission has not. The features displayed by the northern depression are qualitatively similar but

much less clear than those of the western void.

While appealing, the interpretation of the western void proposed in this section leaves a number of questions unanswered, particularly concerning the mechanism responsible for the formation of the equatorial disk. The complexity of the observed features prevents claiming its validity and uniqueness with strong confidence. However, it questions the validity of the interpretation proposed by Homan et al. (2020a) in terms of photodissociation by a white dwarf companion: such a companion should have V_z close to zero, like the disk it is meant to have produced, and should irradiate both the blueshifted and redshifted hemispheres. Additional observations of high sensitivity and angular resolution, including other line emissions, are required to ascertain the validity of either scenario. Additional figures relevant to the description of the western depression region are displayed in Figures S7 to S9 of the supplementary material.

4.4. SiO(5-4) Emission: Patterns of Enhanced Emission

To compare CO(2-1) and SiO(5-4) line emissions, we must limit the radial range and compensate for the different radial declines. In practice, we restrict the analysis to $0.7 < R < 2.0$, also excluding the western sextant $240^\circ < \omega < 300^\circ$ in the blueshifted hemisphere, and divide the observed intensity by a fit of the R distribution to a form AR^b , as was done in Section 4.1. Examples of the resulting maps are shown in Figure 18: one in the blueshifted hemisphere with $b = -0.20$ for CO(2-1) and -1.52 for SiO(5-4), and another in the redshifted hemisphere with $b = -0.76$ for CO(2-1) and -1.20 for SiO(5-4). The normalized brightness has a mean of unity by construction and an rms width that provides a measure of the intensity contrast, which is larger for CO(2-1) than for SiO(5-4): 0.30 and 0.31 for the former, and 0.15 and 0.22 for the latter, in the redshifted and blueshifted hemispheres, respectively.

The correlation between the CO(2-1) and SiO(5-4) normalized maps is illustrated in Figure 18 by plotting, for each pixel, the intensity of the latter versus that of the former. A fit of the form $F_{\text{norm}}(\text{SiO}) = F_0 + G_0 \times F_{\text{norm}}(\text{CO})$ gives a normalized c^2 , with the values of c^2 in the examples shown in Figure 18 being 0.14 and 0.21 in the red- and blueshifted hemispheres, respectively. The value of G_0 , which measures the strength of the correlation, is 0.18 in both hemispheres. The examples displayed in Figure 18 call for several remarks of general validity: the maps of CO(2-1) and SiO(5-4) line emissions display more similarities in the redshifted hemisphere than in the blueshifted hemisphere; small enhancements of emission are seen on both maps, less contrasted on the SiO map than on the CO map; some are common to both maps, while others are seen in only one of the two maps; and in contrast to the higher $|V_z|$ range illustrated in Figure 10, clear arcs are rarely observed.

5. High Doppler Velocities

For a detailed study of the neighborhood of the star and the nature of the high-velocity wings, we use the high-resolution TM0 data in the form of Doppler velocity spectra of SiO(5-4) emission, integrated in 20 mas broad annular rings centered on the star with mean radii increasing from 10 to 390 mas in steps of 20 mas. For each of these we define values of the full width measured at 10% of maximum (FWTM), as sketched in Figure 19(a). This choice of 10% is a compromise between minimizing systematic uncertainties and staying well above noise, and its precise value is of no relevance to the validity of the result. The dependence of FWTM on R gives evidence for confinement within some 200 mas (Figure 19(b)), well described by a fit of the form $21.3 + 19.0 \exp(-R/0.10)$ km s⁻¹. The first term corresponds to the velocity range covered by the bulk of the CSE, the second term to a region of high velocities just above the photosphere, as observed in other oxygen-rich AGB stars and commonly interpreted as resulting from shock waves produced by the interaction of stellar pulsation and convective cell partition (see, for example, Hoai et al. 2020 and Nhung et al. 2022).

We also estimate the maximal Doppler velocity V_{max} reached in the redshifted hemisphere by the bulk of the expanding CSE by extrapolating the upper end of the spectrum down to continuum level (essentially zero) using the combined data. The dependence of V_{max} on R and ω is well described by a fit of the form $V_{\text{max}} = (1.13 - 0.11R) \times [11.1 + 0.8 \sin(\omega - 71^\circ)]$. The rms deviation between data and fit is 0.36 km s⁻¹. Panels (c) and (d) of Figure 19 compare these two factors to the measured mean values of V_{max} , averaged over ω and R, respectively. The dependence on ω corresponds well to what is expected from the tilt of the CSE axis, pointing 20° east of south in the red hemisphere.

This analysis gives two major contributions to the high-velocity wings of the SiO(5-4) Doppler velocity spectrum: one extending up to some 12 km s⁻¹, which is simply the upper edge of the velocity distribution of the polar outflows; and another reaching up to 20 km s⁻¹, confined to the close neighborhood of the star and corresponding to what is observed in most other oxygen-rich AGB stars where this region of the CSE has been carefully explored. The interpretation given by Tuan-Anh et al. (2019) of these high-velocity wings, using data of lower angular resolution, mixed both contributions. This is clearly illustrated in Figure 20, which displays PV maps of $|V_z|$ versus R for both line emissions and both hemispheres separately. In all four cases there is evidence for a clear separation between the two contributions, even if significant differences exist between the CO(2-1) and SiO(5-4) lines as well as between the redshifted and blueshifted hemispheres.

Another illustration is given by the intensity maps displayed in the left panels of Figure 21 for $8 < |V_z| < 12$ km s⁻¹ (combined data) and in the right panels of the same figure for $12 < |V_z| < 20$ km s⁻¹ (TM0 data). The former shows the above-mentioned asymmetry between blueshifted and redshifted hemispheres

along the projection of the CSE axis, while the latter displays instead a small elongation in the perpendicular direction where they are better distinguishable from the bulk. This latter high V_z component seems different from what we know of other stars by the absence of redshifted absorption, usually interpreted as evidence for infalling gas over the stellar disk (Figure 22). Unfortunately, the lack of reliable light curve measurements prevents commenting on a possible relation with the stellar phase at the time of observations.

6. Summary and Discussion

Collecting the information obtained in both the present work and earlier publications to draw a credible picture of the morpho-kinematics of the CSE of EP Aqr is challenging. The interpretation given by Homan et al. (2020a), which gives a major role to a white dwarf companion currently located at 400 mas west of the star, has been shown by the results of the present analyses to be not unique and accordingly less reliable than previously thought. The evidence for a spiral enhancement of CO(2-1) emission and the interpretation of the lumps of CO(2-1) emission in the close neighborhood of the star illustrated in Figure A12 of Homan et al. (2020a) have been shown to become invalid when considering a slightly broader Doppler velocity interval. The detailed study of the blueshifted western depression of SiO(5-4) emission presented in Section 4.3 failed to support an interpretation in terms of dissociation by UV radiation from a white dwarf companion. This does not mean that one can exclude the presence of a companion and its possible role in shaping the CSE. In particular, there is no reason to doubt that EP Aqr, like most other stars, has several planets orbiting it, some of which may already have been engulfed. However, the resulting difficulty in giving a reliable interpretation of the observed morpho-kinematics and the complexity of its many features prevent claiming a credible model of the mechanisms at stake with sufficient confidence.

In general, the global morpho-kinematics of CO(2-1) emission observed in the present work confirms the results of earlier analyses. The evidence for approximate axi-symmetry about an axis making an angle of 10° with the line of sight and projecting 20° west of north on the plane of the sky has been strengthened by observations of both the EDE and polar outflows. The latitudinal dependence of the expansion velocity, evolving from 2 to 10 km s⁻¹ from equator to poles, has been shown to imply a $\sin^n \alpha$ term with n smaller than unity, in contrast with the assumption of $n = 2$ made by Hoai et al. (2019) (Section 4.1). Evidence for enhancements of emission, often but not always with a typical peak-to-valley ratio below a factor of 2, has been found in both EDE and polar outflows, as well as in both CO(2-1) and SiO(5-4) line emissions, though rarely in coincidence. Their morphology in the CO line emission of the polar outflows, taking the form of eccentric arcs, suggests they are caused by shells of mass ejections covering solid angles at steradian scale.

The birth of the equatorial enhancement observed in CO(2-1) emission has been shown to occur very close to the star, first dominated by rotation, then by expansion, becoming particularly clear at distances exceeding 200 mas below which important effective line broadening and dust formation are known to be present (Section 3.1). The lack of evidence for a similar enhancement in SiO(5-4) emission is puzzling; only a very small enhancement is visible at distances exceeding 300 mas (Section 3.2). This suggests that a disk is formed at short distances from the star, probably caused by the presence or recent engulfment of a companion (Privitera et al. 2016), but this is pure speculation. An intrinsic rms width of nearly 1 km s^{-1} has been found to contribute to the EDE flaring of 40° FWHM evaluated earlier (Hoai et al. 2019).

The strong difference between the morpho-kinematics displayed by the SiO(5-4) and CO(2-1) emissions (Section 4.2) was understood as being largely due to the different radial ranges being explored, with the former declining rapidly as a result of accretion by dust grains and dissociation by interstellar UV radiation. In a first approximation, SiO(5-4) emission can qualitatively be described by the standard mass-loss mechanism at play in other oxygen-rich AGB stars (Höfner & Freytag 2019), with a typical terminal radial expansion velocity on the scale of 10 km s^{-1} and some prolateness caused by the presence of the EDE. Indeed, careful inspection of the morpho-kinematics of the SiO(5-4) line emission in the close neighborhood of the star has revealed two distinct broad outflows hosting episodic mass ejections at a timescale of a few decades, covering solid angles at steradian scale, probably associated with shock waves and leaving a depression in their wake. If it were not for the presence of the EDE, the morpho-kinematics of the CSE could be understood as resulting from the standard mechanism of wind generation described by current state-of-the-art hydrodynamical models (Freytag & Höfner 2023).

However, the presence of the EDE causes the CSE to take the form of two polar outflows having increasing radial velocity and accordingly decreasing density when spanning from the equator to the poles. Such a model, suggested by the results of the present analyses, is at significant variance with that proposed by Homan et al. (2020a). To claim its superiority, we would need to understand the details of what precisely causes the progressive disappearance of SiO molecules, what governs the morpho-kinematics of the EDE, what kind of dust takes part in the acceleration process, what are the relative roles of stellar pulsation and convective cell partition in giving the initial boost to the wind, and what pattern of shock waves is present. Only then could one decide with confidence which model is closer to reality. At the present stage, we need additional ALMA observations of high angular resolution and sensitivity to tell them apart. Particularly informative would be observations of molecular line emissions that probe preferentially the very close environment of the star, such as from vibrationally excited states. New infrared observations of the dust, together with simultaneous monitoring of the light curve, are required to possibly reveal correlation with the stellar phase.

Finally, the presence of high-velocity wings extending up to 20 km s^{-1} , previously noted in earlier work, has been confirmed and shown to include two distinct components (Section 5): the upper velocity ends of the polar winds, reaching typically 12 km s^{-1} but with weak tails reaching well above; and effective line broadening confined to distances shorter than 200 mas from the star's center. The earlier interpretation given by Tuan-Anh et al. (2019) failed to distinguish between these two components. The observed line broadening, consistent with similar observations in all other low mass-loss rate oxygen-rich AGB stars observed with sufficient angular resolution and sensitivity, is believed to be due to lumpy emission of shock waves associated with convective cell partition and stellar pulsation, but a detailed picture is lacking.

In general, presently available observations do not allow us to distinguish, in the close neighborhood of the star, the contributions of pulsations, convective cell partition, EDE formation, and dust condensation. EP Aqr is clearly a star from which we should learn more than is currently feasible; it deserves to be studied in as much detail as possible with state-of-the-art instruments. It still leaves us with many open questions, the answers to which would be of great help to improve our understanding of the mechanisms at stake in the generation and development of the wind of oxygen-rich AGB stars.

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Appendix

We show below channel maps of the CO(2-1) emission in both the x versus y plane (Figure A1) and the ω versus R plane (Figure A2). Also shown are PV maps in the Vz versus R plane (Figure A3) and the Vz versus ω plane (Figure A4).

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