PoGO+ polarimetric constraint on the synchrotron jet emission of Cygnus X-1

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We report a polarimetric constraint on the hard X-ray synchrotron jet emission from the Cygnus X-1 black-hole binary system. The observational data were obtained using the PoGO+ hard X-ray polarimeter in July 2016, when Cygnus X-1 was in the hard state. We have previously reported that emission from an extended corona with a low polarization fraction is dominating, and that the polarization angle is perpendicular to the disk surface. In the soft gamma-ray regime, a highly-polarized synchrotron jet is reported with INTEGRAL observations. To constrain the polarization fraction and flux of such a jet component in the hard X-ray regime, we now extend analyses through vector calculations in the Stokes QU plane, where the dominant corona emission and the jet component are considered simultaneously. The presence of another emission component with different polarization angle could partly cancel out the net polarization. The 90% upper limit of the polarization fraction for the additional synchrotron jet component is estimated as <10%, <5%, and <5% for polarization angle perpendicular to the disk surface, parallel to the surface, and aligned with the emission reported by INTEGRAL data, respectively. From the 20–180 keV total flux of 2.6 × 10⁻⁸ erg s⁻¹ cm⁻², the upper limit of the polarized flux is estimated as <3 × 10⁻⁹ erg s⁻¹ cm⁻².

Key words: X-rays: individual (Cygnus X-1) – X-rays: binaries – accretion, accretion discs – techniques: polarimetric

1 INTRODUCTION

Black-hole binaries (BHBs) consist of a stellar-mass black hole (BH) and a companion star. The BH accretes matter from the star, thus forming an accretion disk, corona and jet structures. Although the existence of a jet in a BHB is confirmed observationally (Fender et al. 2004, for a review), the underlying physics (e.g., energetics and formation mechanism) are not yet understood in detail. There are two jet types. One is a ‘transient’ jet, associated with state transitions, and its image is sometimes directly resolvable by radio interferometry. It exhibits superluminal motion and is accelerated close to the speed of light (e.g., Mirabel & Rodríguez 1994; Hjellming & Rupen 1995). The other is a ‘compact’ jet present in the quiescent and hard states. Although not resolved by radio images, the radio emission, which is considered to arise from a self-absorbed synchrotron jet, has a hard spectral index and an infrared flux exceeding that extrapolated from black-body emission of the accretion disk (e.g., Corbel & Fender 2002).

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Cygnus X-1 (Cyg X-1) is one of the persistently bright BH
BHs in our Galaxy (Webster & Murdin 1972). It is pre-
ominantly in the hard state, where the spectrum has a
hard spectral index of \( \sim 1.7 \) and a peak around 100 keV,
i.e., suitable to study the jet physics. Cyg X-1 is a high-
mass X-ray binary with a BH of mass \((15 \pm 1) M_\odot \)
and a supergiant companion star (Orosz et al. 2011; Zdзlowski
2014). The jet structure of Cyg X-1 in the hard state was re-
solved with radio images (Stirling et al. 2001; Fender et al.
2006). Mid-infrared spectral and near-infrared and optical
polarimetric observations are described by synchrotron jet
emission (Rahoui et al. 2011; Russell & Shahbaz 2014). Us-
ing soft gamma-ray spectral and polarimetric information
from the INTEGRAL satellite, the power-law emission above
\( \sim 300 \) keV is reported to be highly polarized, >75%, which
is also ascribed to the synchrotron jet (Laurent et al. 2011;
Jourdain et al. 2012). The GeV gamma-ray spectrum has
been observed by the Fermi satellite. To explain the multi-
wavelength spectral energy distribution (SED), the gamma-
ray emission is proposed to arise from the inverse-Compton
mechanism by high-energy electrons in the jet (Zanin et al.
2016). If the jet produces strong synchrotron emission above
several hundred keV, the strength of the jet magnetic fields
is predicted to exceed the equipartition level (Zdziarski et al.
2014). Although the jet is resolved in the radio domain, its
flux is relatively low in the higher energy band compared to
the companion star, disk and corona in optical, soft X-rays
and hard X-rays (Russell & Shahbaz 2014; Zdziarski et al.
2014). The jet SED of Cyg X-1 is not yet well understood.

Recently, we used the balloon-borne PoGO+ telescope
(Friis et al. 2018) to observe the hard X-ray (19–181 keV)
linear polarization of Cyg X-1 in the hard state. This energy
range is suitable to study the corona emission reflected by
the disk. We have previously shown that the corona geometry
is extended rather than compact (Chauvin et al. 2018).
Such discrimination has not been possible from previous ob-
servations in soft X-rays or soft gamma-rays (Long et al.
1990; Laurent et al. 2011; Jourdain et al. 2012).

In this paper, we extend polarization analyses through
vector calculations in the Cartesian Stokes \( QU \) plane to con-
strain the flux of an additional highly-polarized synchrotron
jet component, as suggested by previous INTEGRAL obser-
vations. We introduce the PoGO+ observations and polarimet-
ric results at other wavelengths and numerical simulations in
§ 2. We start from analyses where the major source of hard
X-rays from Cygnus X-1 is the extended corona in § 3.1.
In § 3.2, we add a possible contribution of the synchrotron
emitting jet to the polarization, and set a limit to the con-
tribution. A low polarization fraction, \( PF \), observed from a
source can result either from a low intrinsic source polariza-
tion, or from cancellation by an additional flux component
at polarization angle, \( PA \), different from the main flux. In
§ 3.3, we confirm that the compact corona model predicts a
high polarization fraction which is inconsistent with the
PoGO+ results, even when considering such a separate emis-
sion component. We present our conclusions in § 4.

2 OBSERVATIONS AND DATA ANALYSES

PoGO+ is a hard X-ray polarimeter which performed
Cyg X-1 observations in the 19–181 keV range (median en-
ergy of 57 keV) during July 12–18 in 2016 (Chauvin et al.
2018). The source was in the typical hard state, based
on light curves by the MAXI (Matsuoka et al. 2009) and
Swift/BAT (Krimm et al. 2013) instruments. Using a pre-
vious Suzaku observation at similar MAXI and Swift
fluxes (Mitsuda et al. 2007), the 20–180 keV flux is estimated
as \( 2.6 \times 10^{−3} \) erg cm\(^{-2} \) s\(^{-1} \) (Chauvin et al. 2018).
At the distance of 1.86 kpc, the luminosity is \( 1.1 \times 10^{37} \) erg s\(^{-1} \), which corresponds to 0.6% of the 15\( M_\odot \)
Eddington luminosity.

Results from the PoGO+ observation of Cyg X-1 give a ‘Maximum A Posteriori’ (MAP) estimate of \( PF = 4.8\% \)
and \( PA = 154\% \), where \( PA \) is measured from North to East
(i.e., counter-clockwise on the sky). This \( PA \) value is consis-
tent with a direction perpendicular to the disk sur-
face. Marginalizing the posterior yields \( PF = (0.0^{+5.6}_{−0.0})\% \)
and \( PA = (154 \pm 31)\% \), where marginalized values are obtained by
projecting the density map onto the \( PF \) and \( PA \) axis,
respectively. The point-estimate and the uncertainty cor-
respond to the peak and the region of highest posterior
density containing 68.3% probability content, respectively.
Details of the PoGO+ polarization analysis are described in
Chauvin et al. (2018).

To measure linear polarization, PoGO+ utilizes the anisotropy of azimuthal Compton scattering events, as
described by the Klein-Nishina relationship. X-rays are more
likely to scatter in the direction perpendicular to the po-
larization, resulting in a sinusoidal modulation curve with
a 180\( ^\circ \) period in the distribution of possible scattering an-
gles (0–360\( ^\circ \)). Results can be transformed to the Stokes \( QU \)
plane using the following relations between \( PF, PA \) and \( Q, U \):

\[
PF = \sqrt{(Q^2 + U^2)} \tag{1}
\]

and

\[
PA = \psi / 2, \tag{2}
\]

where \( Q \) and \( U \) are the fractions of the total intensity \( I \)
parallel and perpendicular to a specific reference direction,
respectively, and \( \psi \) value is the angle from the positive \( Q \)
axis in the \( QU \) plane measured in the counter-clockwise di-
rection. Only a linear polarization fraction is considered (no
circular polarization component, i.e., Stokes \( V = 0 \)). In this
representation, the distance from the origin is equivalent to
the polarization fraction, while the angle \( \psi \) corresponds to
twice the polarization angle. A consequence is that maxima
and minima are separated by \( PA = 90^\circ \) in the modulation
curve, corresponding to \( \psi = 180^\circ \) in the Stokes \( QU \) plane.
In the Stokes \( QU \) plane, two incoherent polarized components
add as vectors, yielding the total \( PF \) and \( PA \) values observed.

In X-ray polarization analyses with a sinusoidal modula-
tion curve, observed ‘detector Stokes parameters’ \( Q/I \) and \( U/I \)
are limited to the range 0–0.5, due to the 180\( ^\circ \) period of the
modulation curve. Multiplication by a factor of 2 is required
to obtain the true ‘source Stokes parameters’ \( Q/I \) and \( U/I \) of
Eq. 1 from the definitions in Kislat et al. (2015); Mikhailov
(2018). We adopt the source Stokes formalism in this paper.

Fig. 1 shows the results from Fig. 2 of Chauvin et al.
(2018) represented in the Stokes \( QU \) plane. The red cross is
the MAP estimate and the red circle corresponds to the
90% credibility region. It is obtained by taking pairs of
\( PF \) and \( PA \) values along the 90% credibility contour and
Table 1. A list of the polarization parameters ($PF$ and $PA$) in the hard state of Cyg X-1 from previous studies. Observational errors are at 1σ confidence level, unless stated otherwise. $PA$ values of simulations assume that the disk rotation axis is parallel with the radio jet direction (158 ± 5°) and include the uncertainty from the radio observations (Stirling et al. 2001; Fender et al. 2006). a Infrared and optical observations include interstellar polarization effects. b Some fraction of the X-ray observations includes data in the soft state but the contribution is not significant. c For 3σ confidence level. d,e See text for details of the simulation setups. d For 20–100 keV energy band. e For 20–50 keV. References (1) Stirling et al. (2001); (2) Russell & Shahbaz (2014); (3) Nagae et al. (2011); (4) Long et al. (1980); (5) Chauvin et al. (2018); (6) Jourdain et al. (2012); (7) Schnittman & Kroll (2010); (8) Dovciak et al. (2011).

| Observations in several bands | $PF$ (%) | $PA$ (°) | Ref |
|--------------------------------|----------|--------|-----|
| 5 GHz                          | < 10     | —      | 1   |
| 1.25–2.12 µm$^a$               | 0.84–1.95| 136.1–142.8| 2   |
| 0.4–0.9 µm$^a$                 | 3.3–5.0  | 134.6–137.6| 3   |
| 2.6 keV$^b$                    | 2.44 ± 1.07 | 162 ± 13 | 4   |
| 5.2 keV$^b$                    | 5.3 ± 2.5 | 155 ± 14 | 4   |
| 19–181 keV                     | < 5.6    | 154 ± 31 | 5   |
| 130–230 keV                    | < 20°    | —       | 6   |
| 200–850 keV                    | 76 ± 15  | 42 ± 3  | 6   |

Simulations in hard X-rays

| Extended Corona$^d$          | 2.5   | 158 ± 5 | 7   |
| Lamp-post Corona (CW)$^c$    | 9–15  | 103 ± 15| 8   |
| Lamp-post Corona (CCW)$^c$   | 9–15  | 33 ± 15 | 8   |

3 RESULTS AND DISCUSSIONS

3.1 Single emission component

In Chauvin et al. (2018), assuming only one emission component, we obtained the $PF$ upper limit at 90% confidence level as <8.6% for the corona emission, by marginalizing over the full $PA$ range of 0–180°. When any $PA$ is allowed, we can determine the 90% $PF$ upper limit to be as large as 11.6% (maximum length from the origin to any point on the red circle in Fig. 1). This occurs when $PA = 154°$ (i.e., $ψ = 308°$ in the $QU$ plane) and corresponds to a direction perpendicular to the accretion disk surface. Similarly, if we consider the emission with a $PA$ direction parallel to the disk surface or aligned with the highly-polarized power-law emission observed in the several 100 keV range, the $PF$ value cannot exceed 2.2% or 2.9%, respectively (intersections between the red circle and the purple region in the 2nd quadrant or the blue dashed region in the 1st quadrant of Fig. 1).

Based on previous spectral and timing analyses (e.g., Done, Gierliński & Kubota 2007), the hard X-ray emission of BHs is dominated by a high-temperature corona emission including its reflection off the accretion disk. There are two main competing models for the corona geometry in the hard state: the extended corona model (e.g., Frontera et al. 2003) and the lamp-post corona model (e.g., Miniutti & Fabian 2004). The former assumes a larger corona size, with the disk being truncated before reaching the innermost stable circular orbit (e.g., Makishima et al. 2008). In the latter model, the corona is assumed to be compact in size and located on the rotation axis of the

![Figure 1. PoGO+ hard X-ray polarization results of Cyg X-1 in the Stokes $QU$ plane. The 90% upper limit corresponds to the circle (red), and its center (red cross) is the MAP estimate ($PF = 4.8\%$ and $PA = 154°$) (Chauvin et al. 2018). Directions parallel and perpendicular to the surface of the accretion disk are in the 2nd and 4th quadrant, respectively. These span a range of $PA \pm 5°$ (i.e., $ψ \pm 10°$ in the $QU$ plane) based on the direction changes of the observed radio jet, which we assume to be perpendicular to the disk surface. Solid and dotted lines correspond to $PA = −5°$ and $+5°$, respectively. The $PF$/$PA$ range predicted for the lamp-post corona model of Cyg X-1 is plotted (green) (Dovciak et al. 2011). The region is defined by the corona height varying 1–20 $R_g$, with the jet direction varying ±5° where solid and dotted lines again correspond to $PA = −5°$ and $+5°$, respectively. Corona heights of 1, 5, 7 and 20 $R_g$ are indicated for the −5° case. Two filled regions are at a corona height 5–7 $R_g$ as estimated from spectral analyses (Fabian et al. 2012). The $PA$ direction (42 ± 3°) of the power-law emission in the several 100 keV range from INTEGRAL observations is shown in the 1st quadrant (blue) (Jourdain et al. 2012). As the INTEGRAL energy range is higher than that of PoGO+ (median 57 keV), they cannot be compared directly, hence the dashed lines.](image-url)
black hole, close to the event horizon. Emission near the black hole is influenced by strong relativistic effects (e.g., Fabian et al. 2012). We concluded that the simple lamp-post corona model was not consistent with PoGO+ polarization measurements and that the extended corona model was favored instead (Chauvin et al. 2018). Other corona models have been proposed (slab, patchy, outflowing, etc.) (e.g., Nowak et al. 2011) although the two main models which we considered can be seen as representative of these.

The extended corona model has a small fraction of the reflection component in the hard X-ray band, and it assumes a lower PF value (~2.5%) with PA perpendicular to the disk surface by numerical simulations (Schmittman & Krolik 2010). Therefore, the PoGO+ upper limit of 11.6% with this PA direction is consistent with the extended corona model.

Conversely, as shown in Fig. 1 and Table 1, the lamp-post corona model predicts higher PF (9–15%) and PA rotation (55 ± 10)° relative to the disk rotation axis due to the strongly enhanced reflection emission (Dovciak et al. 2011). We assume a corona height 1–20 Rₕ, the extreme Kerr case and disk-inclination angle 30°, following X-ray spectral analyses (e.g., Fabian et al. 2012) and the orbital-inclination angle measured in radio (Reid et al. 2011). Here, Rₕ = GM/c² is the gravitational radius, with G being the gravitational constant, M the BH mass and c the speed of light. If the inclination angle is 40° as reported from X-ray analyses (Walton et al. 2016), the simulated PA rotates more (Dovciak et al. 2011) and even separates from the observed MAP PA of 154°. From radio observations, the direction of the orbital rotation is estimated to be clockwise (CW) (Reid et al. 2011). If we assume CW rotation (same direction for the accretion disk as for the orbit), the 55° rotation is subtracted from the PA, yielding (103 ± 15)°. For the counter clockwise (CCW) case, the rotation is instead added, resulting in PA = (33 ± 15)°. In both the CW and CCW case, the resulting PA differs from the PoGO+ measurement. Then, the largest possible PF upper limit of 7.6%, at ψ = 236°(PA = 118°) in the 3rd quadrant of Fig. 1, becomes inconsistent with the predicted level of 9–15% (i.e., the entire 1–20 Rₕ corona height range is incompatible with the PoGO+ data).

3.2 Extended corona emission with a synchrotron jet component

The limits presented in the previous section derive from only assuming one emission component. As described in § 1, polarization observations measure only the total PF and PA (i.e., the summed Stokes vector of the underlying emission components). In the following, we instead examine a situation where the dominant extended corona emission is complemented by a possible synchrotron jet contribution, as suggested by Laurent et al. (2011) and Jourdain et al. (2012).

Although there is no unified picture for the magnetic field in the jet structure, the PA direction is typically assumed to be parallel or perpendicular to the disk rotation axis (Boettcher et al. 2012). It is proposed, from infrared and optical observations summarized in Table 1, that the PA of the synchrotron jet emission can be perpendicular to the disk surface (Russell & Shahbaz 2014). This would correspond to an upper limit on the total emission PFₜotal of 11.6%, arising from Fig. 1 as described previously. Since both the extended corona and the additional component have the same PA direction and the extended corona is predicted to have PF corona of a few percent, the additional synchrotron jet can have PFjet ≤ 10%, such that PF corona + PFjet cannot exceed 11.6%. In this case, the 20–180 keV polarized flux of the jet emission is calculated as <10% of the total flux, i.e., <3×10⁻⁹ erg s⁻¹ cm⁻². Here, we define PF corona and PFjet with respect to the total flux. Simulations assume only corona emission, and we ignore the small change of PF corona due to the contribution of the jet component, as the corona emission is assumed to be dominant throughout this paper.

To derive the actual jet flux (F jet) from the polarized flux, we need to estimate the PF value of the jet emission at the source. If we assume that the jet emission is 100% polarized, F jet is the same as the polarized flux of <3×10⁻⁹ erg s⁻¹ cm⁻². However, if the jet emission has only 10% polarization, which is a typical magnitude for blazar synchrotron jets observed in the optical range (Ikejiri et al. 2011), F jet becomes a factor of (1/0.1) higher than the polarized flux, i.e., <3×10⁻⁸ erg s⁻¹ cm⁻². In this situation, F jet is the dominant component of F total which is inconsistent with the physical picture that the extended corona emission (F corona) dominates.

If the additional jet emission has PA parallel with the disk surface, the 90% upper limit of PF t otal is lower, with the lowest upper limit being 2.2%, as mentioned above. However, in this case, the PA directions are opposite for the extended corona (perpendicular to the disk surface) and the additional component (parallel with disk surface), and PFjet can be as high as ~5%, where PF t otal (~2%) is obtained as PF jet - PF corona (PF corona = 2.5% from Table 1).

We now turn to the case where the additional power-law emission has PA = (42 ± 3)°, as suggested by INTEGRAL SPI measurements for the 230–850 keV region (Jourdain et al. 2012). Polarization results from INTEGRAL IBIS are consistent but have larger errors (Laurent et al. 2011; Rodriguez et al. 2015) and are not considered here. We consider possible combinations of two Stokes vectors yielding a vector sum within the 90% upper-limit circle of the PoGO+ measurement. Fig. 2 illustrates this vector addition, where regions follow from Fig. 1 but text labels have been removed for clarity. Here, the extended corona emission has PA perpendicular to the disk surface locating in the 4th quadrant (purple lines), while the PA for the power-law component from INTEGRAL SPI observations lies in the 1st quadrant (dashed blue lines). The possible vector lengths (i.e., PF values) reach their maximum values when the angle between the two vectors is maximized (maximum cancellation). Following Fig. 2, this happens for the corona contribution line A and jet contribution line B. PF corona is calculated as ~2.5% (vector C with (Q/I, U/I) = (0.015, -0.020) has length 0.025 following Eq. 1) from the numerical simulation (Schmittman & Krolik 2010), in which case PF jet will be limited to <5% (vector D with (Q/I, U/I) = (0, 0.050) has length 0.05), which is where the sum of the two vectors intersects the PoGO+ upper limit.

If we assume that PFjet < 5% from the PoGO+ results and that the jet emission is polarized (76 ± 15)% from Jourdain et al. (2012), then the jet flux will be less than about 8% of the total flux (i.e., F jet < 2×10⁻⁹ erg s⁻¹ cm⁻²).
in the 20–180 keV range, following from $F_{\text{jet}} < 0.05 \times F_{\text{total}} \times (1/0.76)$.

From the SED of Cyg X-1, Zdziarski et al. (2014) estimate the emission of the synchrotron jet component for two cases: several 100 keV flux dominated by the jet, or the non-thermal corona emission. The jet-dominated case corresponds to the above picture for the additional highly-polarized power-law component. The 20–180 keV flux $F_{\text{jet}}$ then becomes $9 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$, where we apply power-law emission with a photon index of 1.6 and a normalization of 0.05 photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$ at 1 keV. This prediction is below the current upper limit resulting from the PoGO+ measurements, meaning we cannot distinguish between jet and non-thermal corona emission dominating the several 100 keV flux.

3.3 Lamp-post corona model with an additional component

We now re-visit the lamp-post corona model, since in the presence of an additional emission component, $P_{\text{Corona}}$ can become higher than $P_{\text{Total}}$, through cancellation by $P_{\text{Jet}}$ perpendicular/parallel to the disk surface or $P_{\text{Jet}}$ from the power-law component by INTEGRAL. We first consider the simple lamp-post corona model with the compact corona height of 5–7 $R_g$ estimated from spectral analyses (Fabian et al. 2012), corresponding to the two filled green regions in Fig. 3 for CW and CCW disk rotation. Auxiliary lines (A’, B’, C’, D’) have been added parallel with their counterparts (A, B, C, D), with magenta lines (A’, A, B, B’) corresponding to $P_{\text{Jet}}$ perpendicular/parallel to the disk surface and blue lines (C, C’, D, D’) to $P_{\text{Jet}}$ from the power-law component by INTEGRAL. For clarity, only lines for CW disk rotation, as from radio observations (Reid et al. 2011), have been drawn (3rd quadrant) although conclusions do not change if the disk rotation is instead CCW (1st quadrant). Lines A’, B’, C’, D’ intersect the filled green region at the side corresponding to corona height 7 $R_g$, where they come closest to the PoGO+ region. Lines A’ and B’ are based on ±5° uncertainty in the radio jet direction, where solid and dotted lines correspond to the uncertainty in the negative and positive direction, respectively. Then, dotted line B’ (±5° uncertainty) cannot intersect at 7 $R_g$ of the top solid green line (−5° uncertainty). Lines C’ and D’ from INTEGRAL observations are independent from the radio jet, and can intersect the filled green region anywhere. None of these lines cross the 90% upper-limit region of the PoGO+ measurement, i.e., the jet PA required to match the PoGO+ data is inconsistent with the three jet directions considered here: perpendicular to the disk, parallel to the disk, and direction as suggested by INTEGRAL results. Therefore, we conclude that the simple lamp-post corona model cannot explain the observational results for Cyg X-1, even when considering an additional emission component.

While a simple lamp-post corona is excluded, there may be more complex cases which this study cannot rule out, e.g., if the corona is outflowing or elongated. If a corona height is close to 1 or 20 $R_g$, which is inconsistent with previous spectral analyses (5–7 $R_g$), it could match the PoGO+ upper limit in the presence of a jet with PA parallel to INTEGRAL power-law component or perpendicular to the disk surface, respectively. More detailed simulations would be required to study such cases.

4 CONCLUSIONS

We have studied the PoGO+ hard X-ray polarization results for the BHB Cygnus X-1 in the Cartesian Stokes QU plane. When only emission from the corona is considered, the extended corona model (low PF and PA perpendicular to the disk surface) is consistent with the PoGO+ 90% upper limit, while the simple lamp-post corona model (high PF and rotated PA values) does not match our observations, reaffirming results from our previous paper (Chauvin et al. 2018).

For corona emission together with a possible synchrotron jet component, we use results in the Stokes QU plane to estimate the upper limit of the jet flux. When assuming a typical PF value of a few percent for the extended corona, the remaining $P_{\text{Jet}}$ can be <5–10% for PA either perpendicular to the disk surface, similar to infrared and optical (Russell & Shahbaz 2014), or PA ~40°, as proposed from INTEGRAL data in the several 100 keV range (Jourdain et al. 2012). The upper flux limit of a highly-polarized jet component is estimated as $F_{\text{jet}} < (2–3) \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$.

Although $P_{\text{Corona}}$ in the lamp-post corona model can be higher through cancellation by a possible component $P_{\text{Jet}}$, the predicted $P_{\text{Corona}}$ value is still too high to explain the PoGO+ results for Cyg X-1.

Current and near-future X-ray polarization missions such as X-Calibur (Kislat et al. 2018) (balloon-borne), AstroSat (Vadawale et al. 2016) and IXPE (Weisskopf et al. 2016) (satellites) can further constrain the jet emission of Cyg X-1. For this, simulations specific to Cyg X-1 (inclination angle, truncated disk radius, etc.) will be re-
required, since current simulations are for generic cases (Schnittman & Krolik 2010). Next-generation gamma-ray missions such as e-ASTROGAM (Tatischeff et al. 2018) and AMEGO are designed with polarimetric capabilities. These will directly confirm the polarization information above several 100 keV, allowing the jet contribution to be determined.

ACKNOWLEDGEMENTS

This research was supported by The Swedish National Space Agency, The Knut and Alice Wallenberg Foundation, The Swedish Research Council, The Japan Society for Promotion of Science, and ISAS/JAXA.

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Figure 3. Vector calculations for the simple lamp-post corona case with a compact corona height of 5-7 \( R_g \). The lamp-post corona model results in \( PF \sim 13\% \) and \( PA \) shifted by \( \sim 60^\circ \) (i.e. \( \sim 120^\circ \) in the \( QU \) plane) relative to the disk rotation axis, resulting from spectral analyses and simulations (Fabian et al. 2012; Dovciak et al. 2011) assuming CW disk rotation (filled green region in the 3rd quadrant) and CCW disk rotation (filled green region in the 1st quadrant). Lines A’ and B’ are parallel with lines A and B which describe \( PA_{\text{jet}} \) perpendicular/parallel to the disk surface. Solid and dotted lines correspond to the jet direction uncertainty of \( \pm 5^\circ \), respectively. Lines C’ and D’ are parallel with lines C and D which describe \( PA_{\text{jet}} \) arising from the power-law component by \textit{INTEGRAL}. 

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