Accretion and Intercycle Variations in the PMS Interacting Binary AK Sco

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Abstract

There are only a handful of known short-period pre-main-sequence spectroscopic binaries with significant accretion rates (Class II sources). AK Sco stands out in this list because the system is composed of two equal mass F5 stars in a highly eccentric orbit thus both stars get as close as 11 stellar radii at periastron passage. This configuration is optimal for accretion studies because enhanced accretion events can be precisely timed at periastron passage. In this work, we present the results from the monitoring of the AK Sco system with Hubble during three consecutive periastron passages. These data provide a unique data set to spectroscopically characterize accretion and evaluate the intercycle variability of the system. Clear evidence of accretion rate enhancement was observed in cycles 1 and 3: the blueing of the near-UV continuum, the sudden flux increase of important accretion tracers, such as the N V, Si IV, and C IV lines, and also of neutral/singly ionized species such as O I and C II. Also, variations in the Si III/C III ratio reveal an enhancement of the electron density by an order of magnitude during the periastron passage. Moreover, in cycle 3, the spectral resolution of the observations obtained with the Cosmic Origins Spectrograph enabled us to discern that the flow was channeled preferentially into one of the two components. The most remarkable feature in the cycle-to-cycle variations was the detection of a notable increase of the UV flux from cycle 1 to cycle 2 that was not accompanied by enhanced accretion signatures.

Unified Astronomy Thesaurus concepts: Interacting binary stars (801); F stars (519); Pre-main sequence stars (1290); Stellar accretion disks (1579); Stellar jets (1607); Circumstellar disks (235)

1. Introduction

Understanding the connection between accretion and outflow during pre-main-sequence (PMS) evolution is a major endeavor in stellar astrophysics and it is required to understand planetary system formation. The high energy spectrum (UV to X-ray) produced through accretion plays a key role in the photoevaporation of the gas in the young planetary disks (see Clarke 2011 and Alexander et al. 2014 for recent reviews) setting the transition between the accreting Class II sources and the weak line T Tauri (WTTS) phase. There are plenty of studies both from the theoretical and observational points of view addressing this process (e.g., Hollenbach et al. 1994; Alexander et al. 2004; Font et al. 2004; Ercolano et al. 2009; Gorti & Hollenbach 2009). There is, however, a need for observations of close binary systems where tidal forces are very significant in the transport of angular momentum hence, in tapping the accretion flow. An additional source of interest relates with the formation and evolution of exoplanetary systems hosting the so-called hot Jupiters; close binaries with low mass ratio, such as UZ Tau, provide important clues on giant planet formation and migration.

Most of the PMS-spectroscopic binaries (PMS-SBs) are low mass systems with primary spectral type G0 or later. In general, the known PMS-SBs are rather evolved objects containing very active young stars (WTTSs) surrounded by thin disks, often debris disks (see Melo et al. 2001 and Gómez de Castro & Marcos-Arenal 2015 for a recent compilation). There are only a handful of PMS-SB that belong to Class II, namely V4046 Sgr, AK Sco, DQ Tau, and UZ Tau E with orbital periods smaller than 20 days, GW Ori with a period of 241.9 days, and CS Cha with a period longer than 2482 days (Guenther et al. 2007). AK Sco stands out in this compilation because the system is composed of two equal mass F5 stars in a highly eccentric orbit ($e=0.47$) that get as close as 11 stellar radii at periastron passage (Alencar et al. 2003). In PMS close binary systems, accretion disks can either take up or release angular momentum and the details of the evolution depend on the mass ratio between the two stars and on the orbit eccentricity (Artymowicz & Lubow 1994; Bate & Bonnell 1997; Hanawa et al. 2010; de Val-Borro et al. 2011; Shi et al. 2012). In particular, AK Sco’s highly eccentric orbit favors the formation of spiral waves within the inner disk; the variable gravitational potential produced by the binary acts as a gravitational piston that drags material efficiently from the inner border of the disk at apastron to release it onto the stars preferentially at periastron (see Figure 1, from Gómez de Castro et al. 2013, hereafter Paper I). Observational confirmation to this prediction has been provided recently by a Hubble monitoring campaign with the Cosmic Origins Spectrograph (COS; Gómez de Castro et al. 2016, hereafter Paper II); coincident with periastron, a marked 10% decrease in the H2 emission from the disk was detected caused by an infalling filament of gas that absorbs the stellar Lyα photons and shades some of the H2 molecules on the disk surface. The light curves also showed an associated enhancement of the main accretion tracers, namely, C IV, Si IV, N V, C III, and Si III resonance UV multiplets (Paper II). AK Sco was also monitored for two more cycles with the Space Telescope Imaging Spectrograph (STIS). All together, the data acquired during these three consecutive cycles provide a unique data set to spectroscopically characterize accretion and evaluate the intercycle variability of the system. The aim of this work is to present the results of this analysis.

The article is organized as follows. A comprehensive summary of the Hubble observing campaign is provided in Section 2. AK Sco was monitored during the first two cycles...
with the Space Telescope Imaging Spectrograph (STIS) providing low dispersion, high sensitivity spectra in the full 1140–3184 Å spectral range; the results from this STIS-based monitoring are described in Section 3. During the last cycle, AK Sco was monitored with COS in the 1159–1762 Å range with much better spectral dispersion (19,000) to study the kinematics of the line emitting plasma and resolve properly the H₂ emission features. The main results from this cycle are gathered in Paper II; however, a detailed description of the kinematics of the radiating plasma is included in Section 4. In Section 5, the data from all three cycles are analyzed together and compared with the predictions from numerical simulations of the dynamical evolution of the binary. STIS data also show evidence of an extended diffuse envelope around the system radiating in Lyα as will be shown in Section 6. All observations were obtained in photon counting mode, this enabled us to study the light curves in detail, especially during the long COS observations. The analysis is included in Section 7 and shows no evidence for short timescale fluctuations (τ ≤ 800 s) neither in the C IV light curve nor in the overall far-UV spectrum. To conclude, a short summary with the main results is presented in Section 8.

### Table 1

| Instrument/Grating | Observation ID | Start Time (JD-2,456,800.0) | Phasea | Exposure Time (s) | Dispersion | Spec. Initial Wavelength (Å) | Spec. Final Wavelength (Å) |
|---------------------|----------------|-----------------------------|--------|-------------------|------------|-----------------------------|---------------------------|
| VISIT 1: STIS/G140L | OCA601010      | 47.740671                   | 0.9924 | 1191.185          | 1190.000  | 1140.000                    | 1730.000                  |
| VISIT 2: STIS/G140L | OCA602010      | 61.341238                   | 0.9918 | 1191.198          | 1190.000  | 1140.000                    | 1730.000                  |
| VISIT 3: COS/G130M  | LCA603010      | 74.952778                   | 0.9920 | 1000.192          | 1900.000  | 1159.478                    | 1435.067                  |
|                    | LCA603020      | 74.967025                   | 0.9932 | 716.200           | 740.000   | 1568.000                    | 1435.067                  |

Note.

*a According to ephemeris in Table 2.

The observations were obtained in 2014 July–August with the Space Telescope Imaging Spectrograph (STIS) and the Cosmic Origins Spectrograph (COS), the log of observations is in Table 1. As shown in Figure 2, AK Sco was tracked during...
During the first two periods, it was observed in low dispersion with STIS and gratings G140L and G230L, to get full coverage in the 1140–3184 Å range with high sensitivity and spatial information. In the last period only the 1159–1762.490 Å range was observed but with higher dispersion (19,000) using the gratings G130M and G160M in COS. Observations were carried out in photon counting mode to preserve as much temporal information as possible and to enable the time series analysis of the results.

The average spectrum of AK Sco during the observing run is displayed in Figure 3. Emission lines formed at a broad range of plasma temperatures are detected as otherwise, usually observed in the ultraviolet spectrum of the T Tauri stars (TTSs; Gómez de Castro 2009): emission from H\textsubscript{2} molecular bands, from the resonance transitions of highly ionized species (N\textsc{v}, C\textsc{iv}, and Si\textsc{iv}), intermediate ionization species (C\textsc{iii}, Si\textsc{iii}, and O\textsc{iii}) and singly ionized or neutral plasma (C\textsc{i}, C\textsc{ii}, O\textsc{i}, O\textsc{ii}, Mg\textsc{ii}, Si\textsc{ii}, and Fe\textsc{ii}). Contributions from the stellar atmosphere, the outflow, and the accretion flow are expected in all of them. The unique feature about Figure 3 is the unprecedented SNR of the UV continuum obtained after coadding all exposures. In Figure 4, the reddening corrected periastron passage in three consecutive periods. During the first two periods, it was observed in low dispersion with STIS and gratings G140L and G230L, to get full coverage in the 1140–3184 Å range with high sensitivity and spatial information. In the last period only the 1159–1762.490 Å range was observed but with higher dispersion (19,000) using the gratings G130M and G160M in COS. Observations were carried out in photon counting mode.
average spectrum \((A_V \approx 0.5, R \approx 4.3, \text{see Table 2})\) is compared with that of the nearby F-type main-sequence stars, HD 139664 and HD 22879 (see the Appendix for details on the UV spectrum of F stars). HD 139664 (F5) is known to have a debris disk but thin enough to have a tiny contribution to the infrared IRAS flux (see Figure 8 in Schneider et al. 2014). Some of the main photospheric features of an F5 star are readily recognized in the AK Sco UV spectrum, as well as the significant excess below 2000 Å. The overall UV spectral energy distribution is closer to a later spectral type (F9) star than to an F5.

3. Results from the STIS Monitoring

3.1. UV Continuum Variability

The UV continuum of F stars in the 1640–3100 Å is very sensitive to the spectral type, as shown in detail in the Appendix. This trend is quantified in Figure 5 where the ratio between the integrated fluxes in the bands: \(F1 (1640–2400 \text{ Å}), F2 (2400–2775 \text{ Å}), \) and \(F3 (2830–3100 \text{ Å})\) has been computed for the F stars in Table 2 and used to build the rates \(R1 = F1 / F2\) and \(R2 = F2 / F3\) represented in the figure. Spectral types of main-sequence stars are indicated, and they define a clear trend parallel to the extinction arrow: extinction is negligible for most of them (see Table 2). Each band traces a main component: \(F1\) is the most significantly affected by extinction (also includes the UV bump), \(F2\) is dominated by the Fe II multiplets, and \(F3\) is dominated by the Balmer continuum and the stellar photosphere. The 55 Å separation between \(F2\) and \(F3\) bands has been set to avoid the very strong Mg II feature. The extinction arrow has been drawn for the average ISM extinction law (Fitzpatrick & Massa 2007), as well for a modified extinction law with \(R = 4.3\) that according to Manset et al. (2005) is representative of the circumstellar environment in AK Sco. Notice that the extinction arrow runs roughly parallel to the spectral types, i.e., there is degeneracy between spectral type and extinction.

We have computed \(R1\) and \(R2\) for all STIS observations of AK Sco (cycles 1 and 2) and overplotted them on the figure. AK Sco is located closer to late F stars than to early F in the diagram though it is classified as an F5 star from its optical spectrum. AK Sco extinction is small, \(A_V \approx 0.5\) (see Table 2) or \(E(B-V) \approx 0.12\), and thus extinction alone cannot account for the observed SED. Henceforth, according to its UV spectrum, AK Sco should be classified as an F8–F9 star instead of the F5 type assigned on the base of its optical spectrum. Moreover, the excess contribution from the accretion flow pushes AK Sco away from the main-sequence band. The variations found during our observing campaign go basically perpendicular to the extinction arrow and are most likely caused by variations in the accretion rate. The integrated UV flux in the 1640–3100 Å spectral range increased by 17% from cycle 1 to cycle 2.

During cycle 1, the excursion of AK Sco in the diagram has a nonnegligible component parallel to the extinction arrow of \(E(B-V) \approx 0.01\), corresponding to a variation in \(A_V \approx -0.043\) (\(A_V = R \times E(B-V)\)): this variation is toward a decreasing extinction or increasing bluing of the spectrum in the middle of the cycle’s observations.
displayed it is concentrated in the cores of the emission lines but there are differences between both cycles:

1. The variability of the most prominent UV lines is a factor of 2 higher during cycle 1 than during cycle 2.
2. During cycle 1, the UV continuum (2630 Å–3150 Å) varies by less than 0.8%; during cycle 2 this variation rises to 2.2%.
3. Not all spectral lines follow the same behavior. For instance, N V variability during cycle 1 is significantly higher than during cycle 2. The same occurs for O III] and Mg II.

The light curves of the main tracers are plotted in Figure 7. Cycle 1 flux variations are reminiscent of those observed in the high dispersion spectra of cycle 3 (see Paper II); at phase ~ 1, at the periastron, there is a sudden increase in the flux that it is observed in N V, Si IV, and C IV but also in singly ionized species such as C II or O I. During cycle 2, variations are softer and within the error bars for most tracers. Clearly, the observed trends change from one cycle to the next. It is noteworthy that the semiferbidden transitions do not follow by the same trends as the permitted lines and their variability is not correlated.

3.3. Flux–Flux Relations and Accretion Shock Diagnostics

Radiation from an accretion shock has a markedly different spectral energy distribution than radiation from a cool star atmosphere. In cool stars, magnetic energy is transported from the stellar surface onto the atmosphere where it is dissipated some 10^4 km/s. The TR is a very thin layer between them. The TR is a very thin layer where the temperature increases by two orders of magnitude and it can only be observed at UV wavelengths. There are well characterized correlations between the flux radiated in the various spectral tracers of these regions; chromospheric (neutral and singly ionized species), TR (C III, Si III, Si IV, C IV, N V, He II, etc.) and coronal spectral tracers (highly ionized species, O VI, X-ray flux, etc.). These so-called flux–flux relations are used to model energy transport in cool stars and call for a universal mechanism operating in them (Ayres et al. 1995; Mihalas 1978).

3.2. Spectral Line Variability

In Figure 6, the spectral variability during cycles 1 and 2 is represented. The variability has been computed as the standard deviation of the mean of the spectra for each cycle, as

\[ \sigma = \sqrt{\frac{\sum_{i=1}^{N}(S_i - \bar{S})^2}{N(N-1)}} \]

Let us denote as \( S_i \) each spectrum and \( N \) the number of spectra obtained in the cycle. The mean spectrum is computed as \( \bar{S} = \frac{1}{N} \sum_{i=1}^{N} S_i \) and the standard deviation of the mean as \( \sigma = \sqrt{\frac{\sum_{i=1}^{N}(S_i - \bar{S})^2}{N(N-1)}} \).

### Table 2
AK Sco Main Parameters

| Property                              | Value                                      | Source                        |
|---------------------------------------|--------------------------------------------|-------------------------------|
| Stellar mass                          | \( M = 1.35M_\odot \)                      | Alencar et al. (2003)         |
| Age                                   | 10–30 Myr                                  | Alencar et al. (2003)         |
| Spectral type                         | F5                                         | Alencar et al. (2003)         |
| Stellar mass                          | \( M_\star = 1.35M_\odot \)                | Alencar et al. (2003)         |
| Radius                                | \( R_\star = 1.59R_\odot \)                | Alencar et al. (2003)         |
| Projected rotation velocity           | \( v \sin i = 18.5 \pm 1.0 \) km s\(^{-1}\) | Alencar et al. (2003)         |
| Bolometric flux                       | \( L_{bol} = 6.33 \times 10^{-6} \) erg s\(^{-1}\) cm\(^{-2}\) | Andersen et al. (1989)        |
| Extinction: \( A_\lambda \)           | 0.5 mag                                    | Manset et al. (2005)          |
| Extinction: \( R \)                   | 4.3                                        | Manset et al. (2005)          |
| Distance                              | 102.8 pc                                   | Schneider et al. (2014)       |
| Radial velocity                       | \( -1.3 \) km s\(^{-1}\)                  | Gontcharov (2006)             |

Figure 5. Variation of the location of AK Sco in the \( R_1 = F1/F2 \) and \( R_2 = F2/F3 \) space during the monitoring run with HST/STIS. The location of main-sequence F stars is indicated as well as the extinction arrow (solid) for the average ISM extinction law (Fitzpatrick & Massa 2007) and the modified extinction law \( R = 4.3 \) found by Manset et al. (2005) to be representative of the circumstellar environment in AK Sco (dashed arrow). Notice that extinction runs roughly parallel to the spectral types. The AK Sco spectrum has not been reddened for the plot but its location close to late spectral types (F7V–F9V) instead of F5 cannot be fully ascribed to extinction; AK Sco extinction \( A_\lambda = 0.5 \) or \( E(B-V) = 0.12 \) (Manset et al. 2005).
Flux–flux relations have also been studied in TTSs (Huélamo et al. 1998; Johns-Krull et al. 2000; Yang et al. 2012; Gómez de Castro & Marcos-Arenal 2012, hereafter GdCMA). When compared with their main-sequence analogs, it becomes evident that there is excess radiation from low ionization species (C II, Mg II, and O I) with respect to the highly ionized ones (C IV, Si IV, and He II). This indicates that radiation is released by a different mechanism than in cool stars. The most successful models propose that the excess gravitational energy of the accreting matter is released into heating at accretion shocks where the temperature reaches 0.3–1 MK, i.e., coronal-like temperatures, driving a photo-ionization cascade that results in the observed scalings (Calvet & Gullbring 1998; Gómez de Castro & Lamzin 1999).

AK Sco monitoring provides a unique chance to evaluate how these scalings behave during an accretion event and hence test the theoretical models. Of the many possible flux–flux relations we should focus on four: C IV versus O I, C IV versus C II, C IV versus He II, and Si III] versus C III]. To study AK Sco behavior in the context of the TTSs properties, all observations of TTSs obtained with HST and STIS G140L and G230L gratings have been downloaded from the Hubble archive and the fluxes of the O I, C II, C IV, He II, Si III]1892, and C III]1908 lines have been determined.

The C IV versus O I flux–flux relation is optimal to evaluate the relative abundance between highly ionized and neutral species in the TTSs environment; it shows the largest deviation from the trend observed in main-sequence stars (see GdCMA). Figure 8 shows that AK Sco falls in the TTSs trend and that from cycle 1 to cycle 2 moves along the trend with the largest fluxes being observed in cycle 2. Both cycles are neatly separated in the plot. Moreover, the intracycle variations are significantly smaller than the intercycle ones. Note that AK Sco fluxes are the sum of the contribution of the two components of the system. To evaluate the contribution from each component is not trivial since according to numerical simulations the accretion flow may be preferentially channeled in any of them (Paper I); splitting the flux in equal parts between the two components is equivalent to shifting by 0.3 dex the location of AK Sco in the diagram.

Cycles 1 and 2 are markedly different. During cycle 2, there are not significant variations in the line fluxes; however, this is not the case in cycle 1, where the OI flux increases by 20% from the beginning to the end of the cycle while the C IV flux increases by ±7% in the same time lapse. The overall flux increase could be accounted for by a decrease in the extinction, but the decrease of the C IV flux at the beginning of the cycle cannot be explained by an extinction effect.

The trends observed in the C IV–O I flux–flux diagram are reproduced in the C IV–C II flux–flux and the C IV–He II flux–flux diagrams (see Figures 9 and 10, respectively). AK Sco observations are located on the regression line of the TTSs in the C IV–C II diagram and they are slightly up in the C IV–He II diagram, similarly to what was observed in the C IV–O I diagram.

The ratio Si III]/C III] is density sensitive and it is often used to measure the electron density of warm plasma in the atmosphere of late-type stars and TTSs (Brown et al. 1984; Gómez de Castro & Verdugo 2001, 2003). In AK Sco, Si III]/C III] ≃ 2, similar to what is observed in the TTSs (see Figure 11), and indicates that the electron density of the emitting plasma is in the range 10^9 to 10^11 cm\(^{-3}\) depending on the precise plasma temperature (see Figure 4, in Gómez de Castro & Verdugo 2001). The Si III]/C III] ratio does not vary significantly from cycle to cycle (2.2 ± 0.6 in cycle 1 and 2.0 ± 0.3 in cycle 2) even though the line fluxes do vary. The first exposure in each cycle has a very good SNR and it can be used as a pivot to measure variations during the cycle. Again, a markedly different behavior is observed between cycle 1 and cycle 2. During cycle 2, no significant variations are observed (1σ and 2σ confidence ellipse are displayed in the plot). However, in cycle 1 there is a significant variation between the...
first exposure (phase 0.9939) and that at phase 0.9993, when the line ratio increases by a 37% and thus the electron density of the plasma.

4. Results from COS Monitoring

The mean profiles of the main transitions are displayed in Figure 12. The profiles are very broad and centered at rest (the
The radial velocity of the system is $1.3 \, \text{km s}^{-1}$). The two spectroscopic components are not resolved in spite of their high relative velocity at periastron passage, from 170 and 190 km s$^{-1}$ during the monitored phase interval (Alencar et al. 2003). The highest asymmetry is observed in the He II transition. As shown in Figure 13, after periastron passage, the line becomes significantly redshifted ($95 \, \text{km s}^{-1}$). This redshift cannot be caused by mass infall. Though, He II is a very sensitive tracer of accretion, He II observations of TTSs show that it is only slightly redshifted, if at all (Gómez de Castro 2013). However, $95 \, \text{km s}^{-1}$ is the expected radial velocity of one of the two components of the system at periapsis, thus the observed shift of the He II flux enhancement indicates that at periastron accretion is preferentially driven into one of the two components.

A similar trend is observed in the rest of the accretion tracers though blurred by the large broadening of the profiles. To visualize it better, we have computed the excess profiles obtained by subtracting the first observation (phase $= 0.9920$ for G130M and phase $= 0.9930$ for G160M) from the rest. In Figure 14, the excess profile is represented as a hyper-surface in phase and wavelength for the main lines. The increase of the redwards shifted component flux from phase 1.0034 on is clearly noticeable in the Si IV, C V, N V, and Si III lines. At the same time, the bluewards shifted component becomes dimmer. This behavior is observed in all hot gas lines, regardless of the COS grating setting or detector segment from which the data were extracted. It is also in marked contrast to the COS observations of H$_2$. The uncertainty of the COS wavelength solution is $\approx 15 \, \text{km s}^{-1}$ (Holland et al. 2014, COS Instrument...
Handbook); therefore, we consider the systematic redshifts of the emission lines to be a real effect. The profiles of the C IV excess are also plotted in Figure 15. They show an increasing absorption in the blue edge of the line that is caused by a progressive decrease of the flux in the bluewards shifted part of the profile compared with the beginning of the periastron passage. One may naively think that this effect is caused by a decrease in the C IV flux (hence the accretion rate) from the companion ($V_{rad} \in [-95, -85]$ km s$^{-1}$); however, the sharp edge at 286 km s$^{-1}$ precludes this interpretation. There is also an H$_2$ emission line on the blue-wing of C IV 1548 (see Herczeg et al. 2002; France et al. 2012); however, variations in the H$_2$ could not have caused the observed edge since the line is very narrow and H$_2$ variability is decoupled from the atomic species (see Paper II).

The light curve of the excess is displayed in Figure 16 for the main spectral lines. The fastest rise is observed in He II; the excess rises by a factor of 4 in one hour. The C IV light curve is significantly softer (excess growth rate of 2.3 per hr). The maximum excess is observed from phase 1.01 on (3.26 hr after periaapsis).

5. Accretion and Cycle-to-cycle Variations

The AK Sco binary system has a highly eccentric orbit; as a result when the system approaches periastron, the outer boundaries of the circumstellar disks (and the accretion streams passing by) get close enough to each other to effectively lose the angular momentum, leading to an increase in the accretion rate. The predictions from numerical simulations for some
sample cycles are shown in Figure 17. Most often, the accretion flow is not evenly distributed between the two components of the system. In fact, there is a pronounced asymmetry in some cycles, see, i.e., cycle 12 in Figure 17. Intercycle variations do not occur only in the total amount of the accretion rate but also in the details of the temporal distribution of the infall that shows in the light curves of the relevant spectral tracers.

The Hubble observations confirm the following predictions:

1. During cycle 1, there is a blueing of the near-UV continuum and an increase of the line flux at phase 0.9982–0.9993 by ∼10%. The increase is pronounced in O I, C II, and Si IV and it is less prominent in saturated (Mg II, C IV) or weak (N V, He II) transitions. This evolution cannot be interpreted as an increase of the fraction of the stellar surface affected by the accretion shock; rather, the variations observed in the flux–flux diagrams call for a variation in the accretion rate and the electron density at the shock front. It is noteworthy that the Si III/C III ratio rises by 37% from phase 0.992 to phase 0.9993 ([1] and [3] in Figure 11) corresponding to an increase of the electron density by a factor of ∼10 for a fiducial temperature of 50,000 K. These observations are consistent with the theoretical prediction of enhanced mass infall (accretion rate) at periastron.

2. During cycle 2, the flux is higher but there are not significant variations during the monitored time lapse.

Figure 12. Mean profiles of the main atomic transitions during the COS monitoring. The rest wavelengths of the atomic transitions are marked for reference; in the O I, S I panel these references are color coded (black O I, orange S I, and blue Si II).
3. During cycle 3, the behavior observed in cycle 1 seems to be reproduced. Moreover, the He II and C IV profiles show evidence of the accretion rate enhancement being channeled preferentially onto one of the two components of the system.

The UV radiation studied in this work is mainly produced at accretion shocks or very close to the stellar surface. Numerical calculations of the structure of accretion shocks in TTSs indicate that the C III], O III], and Si III] lines should have comparable intensities and that their ratios can be reliably used to derive the density, accretion infall velocity, and hence accretion rate on these stars (Gómez de Castro & Lamzin 1999). Though C III] and Si III] transitions could also be excited at the base of the jets (Gómez de Castro & Verdugo 2001), the profiles of these lines in AK Sco clearly indicate that any contamination by a possible jet is negligible (Gómez de Castro 2009), see also Section 6. The location of AK Sco in the Si III]/O III] versus Si III]/C III] diagram is displayed in Figure 18. There are not significant variations during the HST monitoring and, in all cases, the observations indicate that the emission is produced by low temperature (mild shock) and low density (low accretion rate) plasma. The electron density inferred is $(3-4) \times 10^{10}$ cm$^{-3}$ in good agreement with the predictions from generic collisional plasma diagnosis.

The Si III]/O III] ratio varies from $3.2 \pm 0.4$ in the first observation of cycle 1 (the one with the highest SNR) to $2.6 \pm 0.3$ in the first observation of cycle 2. Though this variation is marginal, it is suggestive of a change in the electron temperature from one cycle to another. The Si III]/O III] ratio is temperature sensitive and in the accretion shock scenario, this variation is associated with a small change in the shock velocity, from 200 to 215 km s$^{-1}$. Material in the shock front is heated by the release of the gravitational energy of the infalling material at the impact point, roughly $T \approx \mu v_{\text{shock}}^2/3k_B$. The higher the shock velocity, the higher the electron temperature in the Si III], C III] line formation region. Small variations in the end shock speed are to be expected since the angular momentum of the material in the innermost orbit might suffer slight variations due to the dynamics of the system (see Paper I).

6. Extended Ly$\alpha$ Emission

Ly$\alpha$, Mg II, and semiforbidden line radiation (C II], C III], and Si III]) has been detected from jets and Herbig–Haro objects in TTSs (Coffey et al. 2004; López-Martínez & Gómez de Castro 2015). We used the STIS 52″ × 0″2 slit to enable the possibility of a serendipitous detection of extended outflows from the AK Sco system. The STIS long-slit was oriented at position angles of 28°5 and 36°7 for visits 01 and 02, respectively. The objective here was to build up a signal to look for the spectral signature of extended emission, and consequently all of the STIS G140L and G230L observations were coadded to maximize the chance of detection. The two-dimensional spectra were aligned by fitting a Gaussian profile to the cross-dispersion profile of bright emission regions, C IV and the NUV continuum for G140L and G230L, respectively. The centroids of all the individual exposures were then shifted to the spatial centroid of the initial exposure and the data were stacked. Centroid shifts were ≤2 pixels in all cases. Spatial profiles of several spectral regions of interest were then extracted from the coadded G140L and G230L spectral images.

Figure 19 shows the flux-normalized spatial profiles from the G140L (top) and G230L (bottom) observations. We created individual extractions of H$\alpha$ Ly$\alpha$, C II, Si IV, and the 1427–1520 Å region comprising H$\beta$ emission and FUV continuum, C IV, and O III] from the G140L spectra. Mg II, an adjacent continuum region to Mg II, and two continuum regions dominated by Balmer continuum and stellar photosphere (2000–2620 Å and 2900–3040 Å) were extracted from the combined G230L observations. The Mg II profile is indistinguishable from the adjacent continua. The FUV emission lines (except possibly Ly$\alpha$) are also unresolved, with lines at shorter wavelengths displaying progressively broader profiles at flux levels ≤2% of the peak.
These are likely the result of the extended short-wavelength point-spread function of the HST optical telescope assembly, owing primarily to mid-frequency errors related to the final quality of the telescope polish. The Lyα profile displays both a 1 pixel offset from the main FUV peak and evidence for spatial extension. We caution the reader that these profiles are extracted across the bright geocoronal Lyα emission line—the dotted line profile in Figure 5, top, shows the Lyα profile prior to airglow subtraction and the solid circles are the profile following the subtraction of a constant geocoronal airglow component, the average of 100 pixels centered approximately 4°3 in the “+y” direction on the STIS FUV MAMA. Taking the nominal 103 pc distance (van Leeuwen 2007) and 68° inclination angle (Alencar et al. 2003) for AK Sco, >90% of the FUV line flux is located within ±9.3 au of the center of mass of the system, with >90% of the NUV flux originating within ±7.4 au from the center of mass. Our conclusion is that

Figure 14. Variability of the N V, Si IV, Si III, and C IV profiles during COS monitoring. The evolution of the profile during periastron passage is shown by subtracting the profile at phase 0.9920 from the rest and making a 3D plot. Note that just after periastron, the flux is enhanced. Also a weak absorption develops at high bluewards shifted velocities (250 km s⁻¹). From top to bottom and from left to right: N V, Si IV, Si III, and C IV.

Figure 15. Variation of the C IV profile during cycle 3. The excess C IV emission with respect to the first two observations in cycle 3 is plotted, with 1σ error bars. The rest wavelengths of the doublet lines, at the radial velocity of the AK Sco binary system are marked. The radial component of the orbital velocity of each component is ±90 km s⁻¹ with respect to the systemic velocity. The peak of the C IV, 1550.77 Å line, is redshifted by this amount, similarly to what was observed in the He II line (see Figure 14).
there is tentative evidence that AK Sco displays extended Lyα emission (subject to large uncertainties in the airglow subtraction), but that all of the other emissions originate within $\pm 10$ au of the center of mass.

7. Light-curve Analysis: Search for Low-frequency Modes

In a previous work (Paper I), we reported the detection of an Ultra Low Frequency (ULF) oscillation in the UV light curve from AK Sco using the Optical Monitor (OM) instrument on board XMM-Newton. The ULF oscillation was excited close to the periastron passage, lasting only for a few oscillations at the rise of XMM-Newton. The ULF oscillation was excited close to the periastron passage for the main spectral tracers. The curves have been normalized to the average excess with values of $6.49 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, $1.079 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, $1.311 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, $1.03 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, $2.32 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, and $0.98 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ for Si III, Si IV, C IV, He II, O III, and N V lines, respectively. The average light curve is marked with a thick dashed line.

Gaussian noise. Hence, this significance is usually expressed in terms of a false alarm probability (fap), which encodes the probability of measuring a peak of a given height (or higher) conditioned on the assumption that the data consists of Gaussian noise with no periodic component. A fap level of, say 1%, means that under the assumption that there is no periodic signal in the data, we will observe a peak reaching a level that is as high or higher only 1% of the time.

The COS monitoring of the periastron passage lasts about 9 hr. Figure 20 shows the periodograms corresponding to the light curves (see Paper II). The upper panel corresponds to the G130M data, and the bottom panel to the G160M data. The periodograms are built up to a maximum period of 2.0 hr. The peaks around the rightmost vertical line correspond to the detection of the HST orbital period of around 1.6 hr. The gray area shows the ULF interval as reported in Gómez de Castro (2013). The periodogram panel also plots the horizontal lines corresponding to the required peak height to attain a false alarm probability (fap) of 10%, 5%, and 1%.

In addition to the peaks linked to the HST orbital period, we observe other high peaks. The Lomb–Scargle periodograms detect all periodicities found in the data, including those periods corresponding to the observational sampling period and its $1/n$ multiples. That is, they will also reflect combinations of the duration of exposures and separations between them.

In order to distinguish any real ULF periodicity from those aliased multiples, we have overlaid in the figure the periodograms resulting from fixing the real signal to an arbitrary value of 1. In this way, the pattern of the resulting peaks will exclusively correspond to the observational sampling.

The region where the ULF is suspected to be present is between 0.15 and 0.4 hr. Here, all the peaks are grouped and mimic those found at larger periods, which indicate they are alias from main frequencies. Unfortunately, the typical G160M exposure duration is around 0.22 hr, and these peaks likely come from this sampling duration close to the searched ULF period. The results with G130M data are very similar. Fixing again the counts to an arbitrary unit value, we get the same pattern of peaks resulting from the observational sampling. Finally, when computing the periodograms corresponding to the light curves selecting certain wavelengths, such as C IV, Si IV (Hot species), and C II (warm species), the results are again comparable. Any periodicity within the ULF region may still exist, but with a really high fap, not distinguishable from noise. Outside the ULF region, one may search for other periodicities. But, in a similar manner, all the peaks with low fap are linked to the observing windows, and a clean up process of the sampling frequencies does not improve the results.

As an alternative, we can compute the periodograms just using individual exposures. The signal will be weaker and the fap levels may decrease, but the main sampling multiples will not be present. This analysis is seen in Figure 21. The upper panel shows the results coming from the G130M single exposures. We do not detect any periodicity in the ULF area. The G130M exposure labeled as “isq” presents a peak around a period of 0.17 hr, but the corresponding fap is very high, around 83%, indicating that this could be produced by noise. The G160M analysis also presents peaks with a very high fap. However, as the G160M exposures were taken in consecutive pairs, this analysis uses longer duration light curves. The results can be seen in the bottom panel of Figure 21. The pair labeled “jeq-jgq” presents a peak around 0.25 hr, with a fap of %24. One may think this peak could be an alias of the double exposure duration. But, notably, such a peak is
not present in any of the remaining curves. Hence, we may have a (faint) indication that the ULF was present at least during one of the exposures.

8. Summary and Conclusions

The observations provided by the dedicated Hubble monitoring of AK Sco have enabled for the first time to track the variability of a PMS binary with a degree of detail similar to that of the UV observations of interacting binaries. Much of the observed behavior was already predicted by numerical simulations (Paper I) but this campaign has provided the highly needed experimental evidence of the erratic cycle-to-cycle variations. Also the radiative output from accretion has...
been accurately measured rendering fundamental data for accretion shock calculations.

Two other PMS interacting binaries had previously been monitored with Hubble, namely UZ Tau E and DQ Tau (Ardila et al. 2015), but the phase coverage had significantly poorer temporal resolution and this is a fundamental issue since, as shown in this work, the dynamics of these systems is very complex. Moreover, the gravitational piston effect of the passage by the periapsis is less significant in them making more difficult the precise timing of the accretion events. DQ Tau, the system most similar to AK Sco, is composed of two equal mass stars with mass $0.5 M_\odot$ (Mathieu et al. 1997). The mass ratio of the components in UZ Tau E is 0.289 (Prato et al. 2003) thus mass infall is preferentially channeled in the primary and the effect is less significant.

AK Sco was monitored for two consecutive cycles in low dispersion (high sensitivity) with STIS and a third one with COS providing good time and kinematical resolution at the cost of a lower SNR in the flux. STIS data analysis revealed the enhancement of the accretion rate during the first periastron passage, supported by:

1. Blueing of the 1640–3100 NUV continuum between 0.9982 and 0.9993 phases, in the middle of the cycle.
2. Sudden increase in the flux of important accretion tracers, such as the N v, Si iv, and C iv lines, and also in neutral singly ionized species such as O i and C ii.
3. Variations in the Si iii/C iii] flux–flux diagrams, revealing variations in the electron density by an order of magnitude during the periastron passage.

This behavior is reproduced as well in the third cycle, in agreement with the previous analysis shown in Gómez de Castro et al. (2016). Moreover, the high resolution of COS makes it possible to recognize an increase in the redwards shifted component in important accretion tracers (He ii and C iv), while the bluewards shifted component of these lines decreases, pointing out that accretion is preferentially driven into one of the two components of the system. These intracycle variations are in concordance with the results given in Paper I.

Figure 20. Lomb–Scargle periodograms corresponding to the COS light curves. The upper panel corresponds to the G130M data, and the bottom panel to the G160M data. The gray areas show the suspected ULF period interval. The insets show the periodograms up to a period of 2.0 hr. The dotted pale curves result from processing the exposure signals arbitrarily set to 1, and follow the same patterns that the periodograms resulting from the real signal.
through the XMM-Newton monitoring of the AK Sco system, where the enhancement of the UV and X-ray flux in the binary was suggested to be produced by an accretion outburst. Cycle-to-cycle variations have been measured as well, where the most remarkable feature is the notable increase in the total UV radiation of the system from cycle 1 to cycle 2. Moreover, between the two first cycles, the Si III/O III temperature-dependent ratio reveals a marginal variation of the plasma temperature, which could be translated into a small change in the shock velocity from 200 to 215 km s\(^{-1}\).

Despite the measured enhancement of the UV radiation in cycle 2, the absence of significant variations in the flux of spectral lines and in the flux–flux relations during this cycle reveals no hints about the accretion rate enhancement, in discordance with the other two cycles.

Beside accretion processes in the AK Sco system, the presence of extended emission due the presence of jets has been addressed in this study. Spatial cross-dispersion profiles of STIS data allowed us to identify hints of a diffused envelope around the AK Sco binary radiating in Ly\(\alpha\).

Finally, inspired by the detection of ultra-low-frequency oscillations in AK Sco (Paper I), we analyzed the presence of these low-frequency modes in the light curve of the binary, however, the analysis of the UV light curve from COS data only shows a minor indication that the ULF may be present in the region where the C IV line is produced. This result requires further confirmation with a dedicated campaign monitoring AK Sco only with COS/G160M.

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**Facilities:** HST (COS), HST (STIS).

### Appendix

**The Ultraviolet Spectrum of F Stars**

For the processing and modeling of the UV continuum of AK Sco, and its variability, it is important to compare the UV spectrum of AK Sco with that of F-type main-sequence stars.
For this purpose, we have searched the archive of the International Ultraviolet Explorer (IUE) mission for observations of F stars (IUE object class 41). 924 observations of stars either in the 2000–3200 Å range (cameras LWP or LWR) or in the 1200–2000 Å range (camera SWP) were obtained. We submitted the target list output from the IUE archive to the Centre of Données Stellaires de Strasbourg (program SIMBAD) for the sources cross-identification. We found that about 30% of the observations corresponded to RS Canis Venaticorum systems and spectroscopic binaries. Only single stars with well known spectral types were selected and from those, only stars with high SNR and nonsaturated spectra in the 1200–3200 Å (see Table A1).

The spectra are shown in Figure A1. Three windows can be readily identified: W1(1640–2400 Å), W2(2400–2775 Å), and W3(2775–3100 Å). W1 contains the UV bump and the high energy tail of the spectrum. It is most prominent in early types. W2 is dominated by the Fe II multiplets (2,3,32–36,62,63,363). Flux in W3 increases for the late spectral types as the W1 flux decreases. This permits the use of the rates between the integrated fluxes in these windows, $F(W1)/F(W2)$ and $F(W2)/F(W3)$, as spectral subtype (or effective temperature).
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Table A1

| Star          | Spectral Type | Distance (pc) | (B−V) mag |
|---------------|---------------|---------------|-----------|
| HD 129502     | F2V           | 18.3          | 0.37      |
| HD 26462      | F4V           | 37.0          | 0.36      |
| HD 139664     | F5V           | 17.4          | 0.40      |
| HD 22001      | F5V           | 21.7          | 0.39      |
| HD 30652      | F6V           | 8.1           | 0.44      |
| HD 173667     | F6V           | 19.2          | 0.46      |
| HD 222368     | F7V           | 13.7          | 0.50      |
| HD 126660     | F7V           | 14.5          | 0.51      |
| HD 11007      | F8V           | 27.9          | 0.55      |
| HD 114710     | F9.5V         | 9.1           | 0.59      |
| HD 70907      | F3IV/V        | 286.1         | 0.46      |
| HD 124850     | F7IV          | 22.2          | 0.52      |
| HD 220657     | F8IV          | 52.2          | 0.61      |
| HD 61110      | F3III         | 51.0          | 0.40      |
| HD 57623      | F6II          | 226.2         | 0.79      |
| HD 20902      | F5Ib          | 155.3         | 0.48      |
| HD 171635     | F7Ib          | 649.35        | 0.587     |
| HD 54605      | F8Iab         | 492.6         | 0.68      |

Notes.

a Spectral types, (B−V), and distances (parallaxes) have been extracted from the database in the Centre de Données Stellaires in Strasbourg (France), using the SIMBAD interface.

b Intrinsic (B−V) colors of main-sequence F-type stars range from 0.32 (F0), 0.35 (F2), 0.45 (F5), and 0.53 (F8) (source www.stsci.edu/infr/intrins/johnson.cols).

indicators.

\[
\langle v_{rad} \rangle = \frac{\sum \lambda_c f(\lambda)}{\sum f(\lambda)} - \lambda_0 = \frac{\lambda_0}{c}. \quad (A1)
\]

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