A Binary Model for the Emission Line Star FX Velorum

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Abstract FX Vel is a southern, young variable star which shows large variations in brightness. In examining the environments where planets may form, disks around young stars provide important clues as to how long such disks might last. We discuss several possible scenarios for the structure of FX Vel, including a binary model similar to EE Cep and the possibility that FX Vel may be a UXor variable, a class of young stars with disks. This could also explain the colors and irregular variation in brightness of the star. We suggest FX Vel may be a blue straggler member of the open cluster ASCC48 based upon its position on the cluster CMD and proper motions. More data is required examine the alternate possibility of FX Vel being a member of Teutsch 101. A spectroscopic study of FX Vel would be valuable.

1. Introduction

The formation of planetary systems in different environments is of great importance in informing planet searches of which spectral types are suited to harbor planets. Most searches target dwarfs and it is commonly thought that the short lifetimes of the most massive stars may not allow time for planets to form around them. However, binary systems exist which consist of a B-star and a less massive star where a disk seems to be present around the less massive companion, such as EE Cep (Gałan *et al.* 2012; Mikołajewski *et al.* 2005). In the case of EE Cep, the binary consists of a Be star with a K-type companion. The disk which is responsible for the deep changes in brightness is associated with the lower-mass companion star, rather than the primary, which eclipses the Be star about every five years. The disk around the secondary precesses, changing the contact angle of the eclipse with the disk of the primary. This causes the depth of the eclipse to vary in depth and for the eclipse itself to have a characteristic asymmetric shape (for example, Gałan *et al.* 2012; Graczyk *et al.* 2003). There seems to be a central region that has been cleared out in the disk, causing a short term increase in brightness as the gap passes over the primary.

One reason for addressing this issue is the short lifetime of the Be stars. The Be stars are highly variable optically and have gaseous disks formed around a rapidly-rotating B-type star (Rivinius *et al.* 2013). These stars should last less than a few tens of millions of years before expiring. The current state of the disk around the companions can therefore be compared to models of the disks with these constraints. In addition, the Be stars should not have strayed far from the region they formed, which may include a star forming region or star cluster. As a result, finding the Be star in a cluster should be able to produce an age for the binary, which in turn provides a timescale for the creation of the structures in the disk of the companion star. The secondary star should survive the explosion of the primary, and it is of great interest to know if planets will form and what their fate would be. Identifying analogs of EE Cep for comparison will help address this issue.

FX Vel came to our attention during a search of the All-Sky Automated Survey for variable stars (Pojmański 2004) in the direction of open star clusters. Using the WEBDA Open Cluster Database (Masaryk University 2015) we searched within the radius of open clusters for variables. FX Vel appears in the direction of the cluster ASCC48, identified by Kharchenko *et al.* (2005), although it does lie near the edge of the cluster. The star is bright (V = 9.77), making it accessible to small telescopes. The large, varying eclipse depth and the presence of a massive star suggested possible similarities to EE Cep. We therefore decided to investigate the star further.

FX Vel was first identified as an emission line star by Merrill and Burwell (1950), who did an objective prism survey. FX Vel is their star No. 202 and they give the Hα line as strong. The variable star nature of the star was found in the study of Strohmeier *et al.* (1968), who gave an amplitude 1.20 photographic magnitudes. They classify the star as EW or EB and comment that the secondary eclipses were very deep. They provide a period of 1.052565 days for the system and give ten times of minimum, but do not provide light curves. Heinze (1976) included FX Vel in his catalogue of emission line stars, where it is his star 174. The spectrum is described as having moderately sharp Hα, with a strength lying between moderate and weak compared to the continuum. No note was made about any Hα variability.

Eggen (1978) studied 60 contact systems using photographic observations in the Stromgren and Hβ system. He obtained a spectral type of B9 III-IV for FX Vel and an orbital period of 1.052565 days, based upon a dozen observations. His results did not match those of previous results, showing possibly more than a magnitude-deep primary eclipse. He comments that the Hα observations of Wray (1966) indicate that the emission is weak in FX Vel, which differs from the Strohmeier *et al.* (1968) results. This may suggest Hα variability in FX Vel. Thé *et al.* (1994) include FX Vel as a Herbig Ae/Be star, while Friedemann *et al.* (1996) include FX Vel in their catalogue of binaries with associated IRAS sources. In particular, they include FX Vel as one of their group A stars, which have IR fluxes that vary as λ-1, rather than λ-2 as expected from a purely stellar spectrum. They conclude the presence of circumstellar dust around these types of stars. Tisserand *et al.* (2013) give a spectral type of A3III for FX Vel.

Most recently, Miroshnichenko *et al.* (2007) investigated FS CMa stars and included FX Vel as a member of this group.

FS CMa stars are B[e] stars which are also associated with dusty disks, many of which have lower-mass companions. One characteristic of the FS CMa stars is the unusual infrared emission in their spectra which suggests on-going formation of dust. These stars also tend to lie in the field, away from sites of current star formation. Miroshnichenko *et al.* (2007) point out the contradictory studies of the amplitude of variability of FX Vel, and note that their examination of the ASAS light curve rules out the short 1.05-day orbital period found by Strohmeier (1968) and Eggen (1978), since the minimum which occurred around JD 2452000 lasted for more than two months. Miroshnichenko *et al.* (2007) suggest the irregular light curve is similar to other isolated Ae/Be stars except for the lack of reddening. The spectra of Miroshnichenko *et al.* (2007) were taken in December 2004 and show double-peaked profiles in their Balmer lines with stronger blue-ward emission. They suggest this may indicate perturbations in the disk around the Be star.

2. Cluster membership

The original reason for FX Vel drawing our attention was that it is within the search radius of the cluster ASCC48 when searched with the WEBDA open clusters database. Kharchenko *et al.* (2005) searched for unidentified open clusters and identified 109 new open cluster candidates. ASCC48 has not been studied since. If FX Vel is associated with a cluster this could provide an age estimate of the star. We note that a cluster this age is likely too old to host a Be star (for example, Tarasov and Malchenko 2012). The possibility is that FX Vel does not contain a Be star, given the spectral type of A3III, as discussed in section 3. Figure 1 shows the color-magnitude diagram of ASCC48, with FX Vel indicated. We plot the isochrones from the Padova group (Bressan *et al.* 2012) using the parameters obtained by Kharchenko *et al.* (2005), log age = 9.1, E(B–V) = 0.00, V – Mv = 8.01, and include the photometry from the study of Kharchenko *et al.* (2005). We include isochrones with Z = 0.019, 0.008, and 0.004, with the Z = 0.019 matching the CMD best. A spectroscopic study to obtain the metallicity of the cluster would be helpful. There is large scatter present, but FX Vel does not appear to be a main sequence member of this cluster although it may be a blue straggler. To investigate this further we compared the proper motion of FX Vel to that of the cluster members. In Figure 2 we show the proper motions μ_α and μ_δ of cluster members with greater than 50% probability of membership based on proper motions (Kharchenko *et al.* 2005), as well as the proper motion of FX Vel from Tycho-2 (Høg *et al.* 2000). FX Vel is close to the region occupied by the probable cluster members and is closer to the cluster of points than others which have a greater than 50% probability of being members. We conclude that if FX Vel is a cluster member, it is most likely a blue straggler. However, many stars that appear to members based upon their photometry are excluded based upon proper motions in the WEBDA database, so a radial velocity study would be useful. We can't conclude whether FX Vel is a member or not.

Another cluster near FX Vel is DSHJ0832.5-3807 (Teutsch 101), identified by Kronberger *et al.* (2006) using 2MASS data.

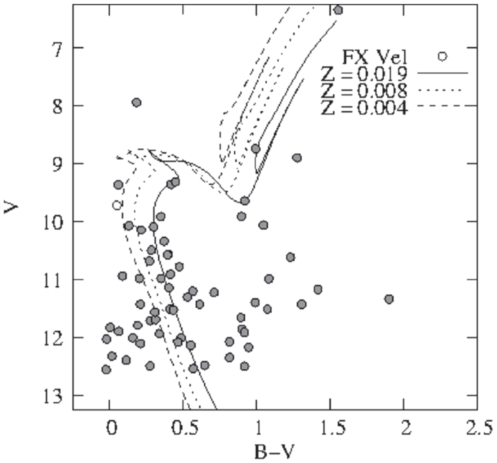

Figure 1. The Color-Magnitude Diagram (CMD) of ASCC 48 with FX Vel. We include the photometry of cluster members from Kharchenko *et al.* (2005) and isochrones from Bressan *et al.* (2012). The best match to the main sequence and the giant branch of the cluster is that for Z = 0.019. FX Vel (open circle) does not appear to be a cluster member unless it is a blue straggler.

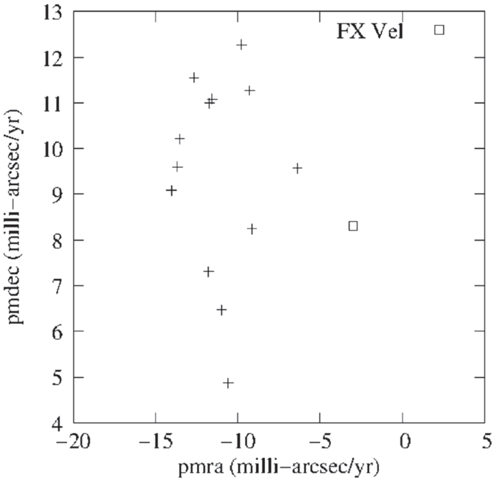

Figure 2. Proper motions of members of ASCC 48 with greater than 50% probability of membership based upon their proper motions (crosses). FX Vel (square) is also plotted and does not appear to be an outlier, implying membership. A radial velocity study would help determine if FX Vel is a member or not.

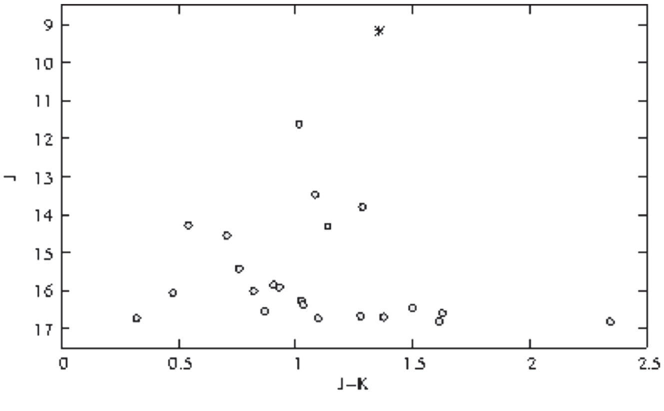

Figure 3. A J versus J-K CMD from the 2MASS database the stars within 1 arminute of the position of Teutsch 101 given in Table 2. The star indicates the position of FX Vel while the circles show data for the stars near the cluster center. FX Vel appears brighter but redder than the candidate cluster stars, but without membership probabilities, reddening, and distances it is difficult to draw any conclusions from this comparison.

Table 1. Data from 2MASS on point sources within the cluster radius of Teusch 101. Null errors are flags given when the magnitude is a 95% confidence upper limit.

2MASS Identification	*R.A. (J2000) h m s*	*Dec. (J2000) ° ' "*	*J*	*σJ*	*H*	*σH*	*K*	*σK*
08323442-3807212	08 32 34.43	–38 07 21.24	14.310	0.030	13.466	0.033	13.173	0.032
08323204-3807271	08 32 32.05	–38 07 27.13	16.596	0.128	15.742	0.116	14.969	null
08323675-3806253	08 32 36.75	–38 06 25.39	16.730	0.153	16.317	0.188	15.634	null
08323203-3807520	08 32 32.03	–38 07 52.07	16.013	0.072	15.158	0.058	15.192	0.168
08323476-3806519	08 32 34.77	–38 06 51.97	16.540	0.116	16.410	0.195	15.672	0.265
08323091-3807198	08 32 30.92	–38 07 19.89	14.277	0.036	13.883	0.032	13.734	0.054
08323143-3807415	08 32 31.43	–38 07 41.51	16.373	0.111	15.761	0.120	15.342	0.199
08323403-3807013	08 32 34.03	–38 07 01.37	15.912	0.061	15.181	0.063	14.980	0.139
08323492-3807137	08 32 34.92	–38 07 13.77	14.550	0.047	14.060	0.058	13.843	0.060
08323704-3806504	08 32 37.04	–38 06 50.46	16.670	0.152	16.414	0.218	15.392	null
08323204-3807040	08 32 32.04	–38 07 04.06	15.422	0.043	15.009	0.058	14.663	0.114
08323158-3806397	08 32 31.59	–38 06 39.74	16.729	0.148	16.359	0.190	16.408	null
08323250-3807170	08 32 32.50	–38 07 17.01	16.817	0.160	16.144	0.296	14.475	null
08323143-3807065	08 32 31.44	–38 07 06.56	16.063	0.075	15.457	0.079	15.586	0.248
08323331-3806572	08 32 33.31	–38 06 57.23	13.474	0.026	12.688	0.024	12.390	0.021
08323526-3807069	08 32 35.27	–38 07 06.99	16.699	0.155	16.307	0.218	15.323	null
08323497-3807196	08 32 34.97	–38 07 19.63	13.799	0.039	12.891	0.046	12.513	0.030
08323094-3807131	08 32 30.94	–38 07 13.15	16.451	0.112	15.721	0.111	14.954	null
08323305-3807152	08 32 33.05	–38 07 15.29	11.611	0.027	10.865	0.026	10.596	0.021
08323746-3806251	08 32 37.47	–38 06 25.14	16.805	0.154	16.174	0.160	15.193	null
08323369-3806513	08 32 33.70	–38 06 51.40	15.848	0.069	15.268	0.074	14.942	0.142
08323439-3806393	08 32 34.40	–38 06 39.37	16.265	0.094	15.436	0.077	15.241	0.171

We investigate here if FX Vel might be a member of this group. We do not have a reddening, age, or distance estimate or proper motions for this cluster, so we are left with producing a CMD from the stars in the 2MASS database within 1 arcminute of the cluster coordinates given by Kronberger *et al.* (2006). We give the data from the 2MASS database of these stars in Table 1, and the CMD in Figure 3. Interpretation of this plot is difficult with so few stars, but FX Vel is nearly two magnitudes brighter and is redder than the next brightest object which suggests it is too bright to be a member. Without estimates of reddening of each star to correct the colors this conclusion is not very secure so this comparison is inconclusive.

3. The Nature of FX Vel

3.1. Is FX Vel a binary?

As commented on by Miroshnichenko *et al.* (2007), the ASAS (Pojmański *et al.* 2013) has collected several years of data on FX Vel. They rule out the 1.05-day orbital period of the system based on their examination of the length of minimum in the light curve. Since that time, the ASAS has produced more observations of FX Vel, which we consider here. Figure 4 shows the light curve of FX Vel from the ASAS. The striking feature of this dataset is that the dips are varying in both depth and in shape, with considerable variability on each one. This is not easy to explain with a simple eclipse model, and we propose here that what is being observed is the eclipse of the primary star by the precessing disk of a cooler companion. This is similar to the model used to explain the changing shape and depth of the dips in EE Cep.

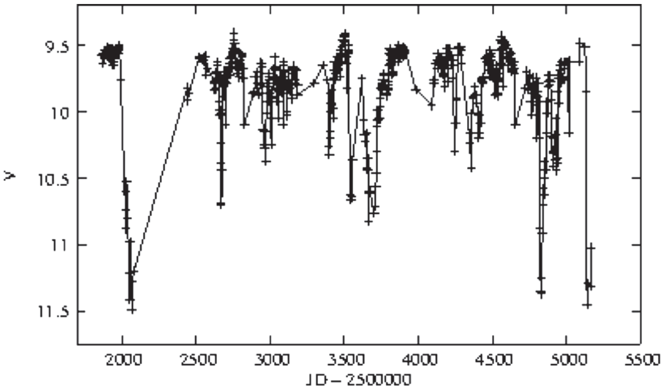

Figure 4. The light curve for FX Vel from the All-Sky Automated Survey (ASAS; Pojmański *et al.* 2013). FX Vel undergoes drops in brightness or more than 1 to 2 magnitudes, with some events deeper than others.

Figure 5 shows the data for several brightness dips. The first dip in brightness (Figure 5 top left) is asymmetric, with the drop to minimum light taking longer than the subsequent rise to maximum brightness. Interestingly, the dip in brightness is preceded by a shallow drop in brightness. The following dip in brightness (Figure 5 top right) is a double-dipped event. The first dip in brightness has a slight drop in brightness followed by a very steep drop to minimum light. Unfortunately the following increase in brightness is not covered by the ASAS monitoring. Following this is another dip in brightness, which starts apparently even before maximum brightness is reached. The dip in brightness has several individual fluctuations on a small scale and the slope gets shallower towards minimum light. The brightness first rises sharply and then slowly reaches maximum light. The slow rise has several dips in brightness as well. The third event (Figure 5 bottom left) which we show is poorly measured, but is also preceded by a shallow drop in brightness and appears symmetric. It is very similar to the first. The final event (Figure 5 bottom right) looks similar to the second, but is nearly a magnitude deeper. There is first a very rapid decrease in brightness, followed by an increase in brightness that changes slope. There is then a shallower, less deep drop in brightness after the initial dip in brightness. The shallower drop in brightness is also double-dipped with a peak in the center of the eclipse.

We hope to understand why there appear to be two types of events for FX Vel, and why some dips in brightness appear to occur in pairs or with shallower events following or preceding them. If the secondary star has a disk around it that is warped by the gravity of the primary the variations in brightness can be understood (Figure 6). The greater the amount of the disk that intercepts light from the primary the greater the drop in brightness and the longer the drop in brightness will be. However, if the disk is precessing, the orientation of the disk can change. In the first case (Figure 6 top) the disk of the primary intersects the disk at three points, creating first a short, shallow brightness drop followed by a longer, deeper eclipse. In the second case (Figure 6 middle) the precession of the disk creates geometry in which the primary intersects the disk at only one location, resulting in a short shallow drop in brightness only (Figure 6 middle). In the final example (Figure 6 bottom) the disk of the primary intersects the disk at three points, but the longer, deeper event precedes the shorter, shallower drop in brightness.

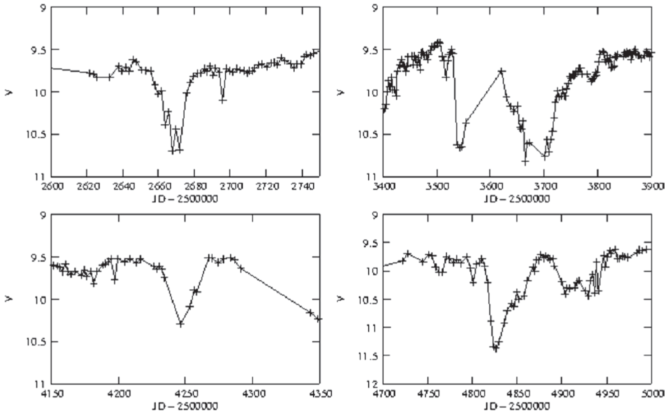

Figure 5. Four eclipse events for FX Vel showing the variety of changes in the eclipses. The first eclipse (top left) is slightly asymmetric, with the drop in brightness being slightly longer than the following increase in brightness after light minimum. The second eclipse (top right) has partial coverage of the first decrease in brightness, but the initial drop in brightness is very rapid. The following drop in brightness is at first rapid and then becomes less shallow near the bottom of the eclipse. The subsequent increase in brightness is rapid followed by a slower increase. The third eclipse (bottom left) has relatively poor coverage, but appears symmetric. The fourth eclipse (bottom right) has a rapid drop in brightness with a slower increase. This is followed by a shallower eclipse that also exhibits an increase in brightness near the bottom.

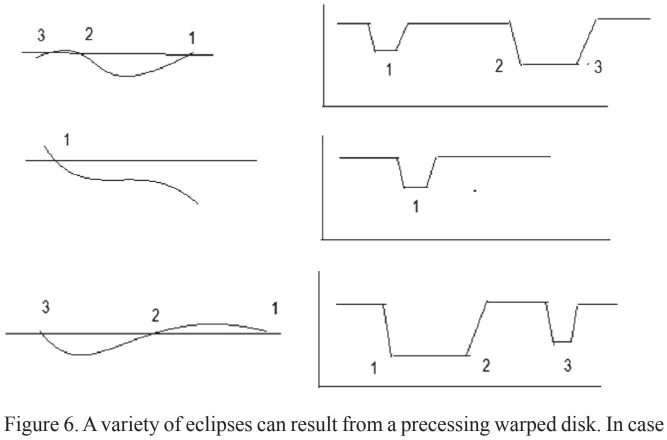

Figure 6. A variety of eclipses can result from a precessing warped disk. In case one (top), the disk of the primary will intersect the disk at three points, resulting in first a short, shallow eclipse followed by a longer, deeper eclipse. In case two (middle), the primary will intersect the disk at only one point, resulting is a single shallow eclipse. In case three (bottom), the primary first intersects the disk creating a longer deep eclipse followed by a short, shallow eclipse. The variety and varying depth of the eclipses seen in Figure 4 is reproduced. The disk may also have a gap in it, and may vary in thickness, making the shapes of the eclipse asymmetric.

If the primary star has a binary companion, then the secondary star may orbit out of the plane of the disk of the primary, and the secondary's disk will form along the equatorial plane of the secondary star. Miroshnichenko *et al.* (2007) obtained an Hα spectrum of FX Vel which shows a central dip surrounded by emission peaks with a stronger blue peak than red. Rivinius *et al.* (2013) suggest that this form of spectrum is observed when the Be star is seen through the plane of the disk from the perspective of Earth. Any difference between the plane of the orbit and that of the disk around the companion will cause precession in the disk of the secondary. As the binaries orbit, the orientation of the disk will be changing from our perspective. A very variable light curve results from these combined changes.

One serious problem with the binary model is that the dips in brightness are very long. If solely caused by orbital motion of the secondary as the disk passes in front of its companion, the disk would seem to be overflowing the Roche lobe of the secondary, or be bigger than the binary system itself. This is difficult to reconcile.

3.2. Is FX Vel a UX Ori variable?

An alternative explanation has been proposed by S. A. Otero in his remarks on FX Vel in the AAVSO International Variable Star Index (VSX; Watson *et al.* 2014). The UXor variables are a class of young stars in the pre-main sequence stage of evolution. The stars are emission line A-type stars which exhibit several magnitude drops in brightness (Herbst and Shevchenko 1999) for up to several days or weeks. Dullemond *et al.* (2003) interpret the brightness variations as being caused by density variations in a disk around the star causing greater or less absorption of the light from the star. This mimics the drops in brightness of FX Vel. In addition FX Vel has colors (Table 2) that resemble the class of UXor variables more so than EE Cep. Tisserand *et al.* (2013) give a spectral type of A3 IIIe for FX Vel as well, similar to the UXor stars. We include the infrared colors of Be star γ Cas for comparison. Clearly FX Vel has colors more similar to the UXor variables than the Be stars. However, also for comparison, we include the colors of EE Cep, whose light curve resembles that of FX Vel. EE Cep, as we have noted, contains a Be star and a low-mass companion with a disk in which the precession of the disk causes variations in the eclipse depths and lengths. EE Cep has colors that do not match FX Vel well, so its IR colors would seem to argue against an interpretation of FX Vel's light curve variations being caused by a precessing disk around a companion. Observing campaigns would be useful for FX Vel to study variation in Hα and colors during the drops in brightness.

Table 2. Infrared Measurements of UXor stars, FX Vel, and γ Cas.

Star	*Wavelength/Band (μ)*							
	W1 *3.35*	*W2* *4.6*	*W3* *11.6*	*W4* *22.1*	*J* *1.25*	*H* *1.65*	*K* *2.17*	*J–W4*
BF Ori	6.84	6.05	3.59	2.20	9.11	8.57	7.90	6.91
SV Cep	6.74	5.98	2.55	0.75	9.35	8.56	7.74	8.60
UX Ori	6.24	5.51	2.92	0.92	8.71	8.04	7.21	7.79
WW Vul	6.58	5.95	3.33	1.56	9.09	8.18	7.28	7.53
XY Per	4.92	3.79	2.55	0.97	7.65	6.92	6.09	6.68
FX Vel	6.53	5.56	2.41	1.05	9.17	8.66	7.81	8.12
γ Cas	1.67	0.45	0.04	-0.30	2.04	1.99	1.76	2.34
EE Cep	7.24	6.70	5.99	5.60	9.60	9.22	8.56	4.00

4. Conclusions and future work

We have examined the star FX Vel and have concluded more data are required to determine if it is a member of the galactic star cluster ASCC 48 based upon its location on the CMD of the cluster and its proper motion. Likewise more data are needed to determine if FX Vel is a member of Teutsch 101. Radial velocity studies of these clusters and FX Vel would be very helpful in resolving this. The light curve of FX Vel has been re-examined and we suggest two possible models to explain the properties of its photometric variability. In one model the changes may be explained by the presence of a precessing disk around the secondary star which intercepts differing amounts of light as each orbit of the secondary occurs. The double dip of one eclipse suggests that the disk may have a warp in it that allows only partial coverage of the primary disk during eclipses at some times. In the second model, supported by the IR colors and length of the eclipses, FX Vel is a UXor variable with a star surrounded by a disk with differing densities. FX Vel has been relatively poorly studied and a great deal could be done to help improve our understanding of this star. We do not have color information for the dips in brightness of the star of the star. We expect that the color should be redder if a disk is causing the large variable brightness changes. Photometric monitoring in multiple bands should be carried out to provide these data. In addition, spectra are needed to study the variation of the spectrum at Hα. Polarization studies before, during, and after eclipses might also help study the properties of the dust.

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