X-RAY AND OPTICAL VARIATIONS IN THE CLASSICAL Be STAR γ CASSIOPEIA: THE DISCOVERY OF A POSSIBLE MAGNETIC DYNAMO

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ABSTRACT

The classical B0.5e star γ Cassiopeia is known to be a unique X-ray source by virtue of its moderate L_X (10^{33} ergs s^{-1}), hard X-ray spectrum, and light curve punctuated by ubiquitous flares and slow undulations. The peculiarities of this star have led to a controversy concerning the origin of these emissions: whether they are from wind infall onto a putative degenerate companion, as in the case of normal Be/X-ray binaries, or from the Be star itself. Recently, much progress has been made to resolve this question: (1) the discovery that γ Cas is a moderately eccentric binary system ($P = 203.59$ days) with unknown secondary type, (2) the addition of *RXTE* observations at six epochs in 2000, adding to three others in 1996–1998, and (3) the collation of robotic telescope (Automated Photometric Telescope) *B*- and *V*-band photometric observations over four seasons that show a 3%, cyclical flux variation with cycle lengths of 55–93 days. We find that X-ray fluxes at all nine epochs show random variations with orbital phase, thereby contradicting the binary accretion model, which predicts a substantial modulation. However, these fluxes correlate well with the cyclical optical variations. In particular, the six flux measurements in 2000, which vary by a factor of 3, closely track the interpolated optical variations between the 2000 and 2001 observing seasons. The energy associated with the optical variations greatly exceeds the energy in the X-rays, so that the optical variability cannot simply be due to reprocessing of X-ray flux. However, the strong correlation between the two suggests that they are driven by a common mechanism. We propose that this mechanism is a cyclical magnetic dynamo excited by a Balbus-Hawley instability located within the inner part of the circumstellar disk. According to our model, variations in the field strength directly produce the changes in the magnetically related X-ray activity. Turbulence associated with the dynamo results in changes to the density (and therefore the emission measure) distribution within the disk and creates the observed optical variations.

Subject headings: circumstellar matter — stars: emission-line, Be — stars: flare — stars: individual (γ Cassiopeiae) — ultraviolet: stars — X-rays: stars

1. INTRODUCTION

Since its discovery in 1867, γ Cassiopeia has become the prototype of the "classical" Be stars. However, while the optical properties are representative of the class, its behavior in the X-ray regime is not just unusual but so far unique. Its mean L_X is a few times greater than any other Be or B-normal stars but at least a factor of 20 lower than in Be/X-ray binaries. The X-ray light curve is especially interesting in that it is composed of numerous, short-lived bursts (with durations of 10 s to 1 minute) superimposed on a background ("basal flux") that varies in intensity by a factor of up to 3 over timescales ranging from hours to months. The X-ray spectrum is hard, being consistent with a thermal 10.5 keV thin plasma, and it shows Fe lines at 6.7 and 6.9 keV.

In the past the commonly accepted explanation for the X-ray emission involved mass accretion onto a putative degenerate companion, either a neutron star (White et al. 1982) or a white dwarf (Murakami et al. 1986). There are

some problems with this interpretation (see Smith, Robinson, & Corbet 1998, hereafter SRC98, and Robinson & Smith 2000, hereafter RS00, for discussions of the binary hypothesis), and Smith (1995) published an alternative picture in which the anomalous X-rays were generated by energetic flares near the star's surface. To test this hypothesis, SRC98 organized a coordinated observing campaign in 1996 March involving the *Rossi X-Ray Timing Explorer* (*RXTE*) and the *Hubble Space Telescope*, where the Goddard High Resolution Spectrograph (GHRS), with large aperture, was used to obtain high time resolution spectra covering 40 Å centered on the Si IV lines near 1400 Å. The object of the program was to look for correlations between X-ray variations and changes in the UV continuum and the Si IV line profiles. Since any UV variations are likely to originate at or near the Be star, a strong correlation with the X-rays would provide evidence that the X-rays are also emitted from near the star.

The program proved to be highly successful and showed a pronounced *anticorrelation* between the intensity of the basal X-ray flux and the value of the UV continuum near 1400 Å (see SRC98), an anticorrelation with the Si III and Si IV (low-excitation) ions' line strengths, and a direct correlation with the high-excitation Fe V line strengths (Cranmer, Smith, & Robinson 2000).

The basal X-ray flux from the 1996 March observations was found to vary on a ~10 hr timescale (Fig. 1a). UV observations obtained during *International Ultraviolet Explorer* (*IUE*) campaigns in 1982 and early 1996, combined with the GHRS results, showed a UV continuum

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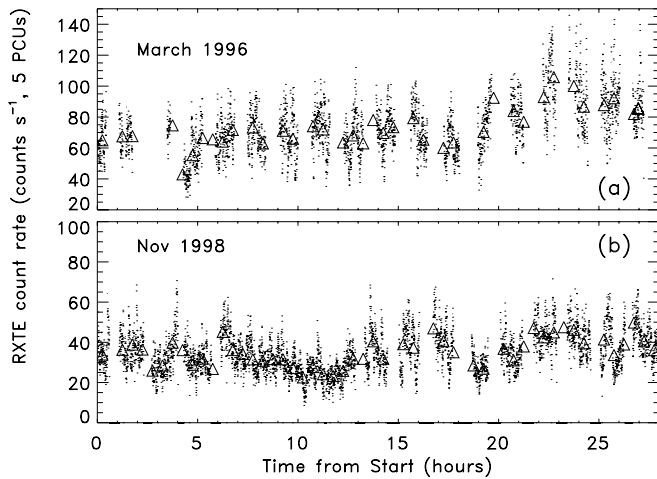
Fig. 1.—Summary of *RXTE* observations taken in (*a*) 1996 March and (*b*) 1998 November. Filled circles represent 16 s averages, while triangles are 30 minute averages. The uncertainties in the data can be represented by Poisson statistics. Thus, errors in the position of the triangles are much smaller than the symbols. Each plot represents a single 27 hr rotation cycle.

modulation of 27 hr. This is in agreement with the expected rotation period of 22–30 hr given the star's known $v \sin i$ and estimated radius (see, e.g., Cranmer et al. 2000). Thus, SRC98 suggested that the X-ray variations are attributable to a rotational modulation of active magnetic complexes on the stellar surface. To confirm this interpretation, the *RXTE* was used on 1998 November 24–26 to search for a reoccurrence of the variation pattern over two rotation periods. A summary of part of this time history is given in Figure 1*b*. Comparison of the two panels of this figure discloses that the light-curve characteristics changed markedly between 1996 and 1998. The 1998 fluxes were substantially lower than those seen in 1996 March, while the timescale of variation had decreased to 3–4 hr. No clear signal for rotational modulation was discovered (see RS00). However, RS00 found that the X-ray fluxes did undergo a partial cessation every ≈7.5 hr. This behavior was intriguing since archival *IUE* data showed marked strengthening of the high-velocity Si IV and C IV wind features (discrete absorption components) with the same cyclicity. The rapid timescale for the basal flux variability also points to a rapid evolution of the activity centers, which would mask any rotational modulation.

The dramatic changes in these X-ray light curves were unexpected. The authors concluded that more observations were needed in order to quantify the timescale and form of these variations. It was also hoped that the nature of the variations could be better understood by comparing the X-ray results with other parameters of the star, such as the one-armed density enhancement in the Be disk, which is known to be responsible for the 5–7 yr cyclic variations of the Hα emission profile (Telting & Kaper 1994; Berio et al. 1999). Thus, an observing program using the Automated Photometric Telescope (APT) was initiated to monitor the optical variability of γ Cas in the Johnson *B* and *V* bands. New *RXTE* observations were also carried out in 2000, consisting of six time sequences spaced at increasing intervals from 1 week to 5 months. It is these optical and X-ray data that will be examined in this paper.

In § 2 we describe briefly the X-ray and optical observations and reduction procedures. The long-term variations

are then described in § 3. Here it is shown that both the X-rays and optical fluxes show cyclic fluctuations on a timescale of 55–93 days. The X-ray and optical variations also appear to be strongly correlated. The short-term variations are then discussed in § 4. Here we examine the short-term changes in the X-ray flux and compare them with similar variations seen in the optical region. Many of the X-ray time sequences appear to have broad flux minima that are repeatable. These features are used as markers in attempting to determine the stellar rotation rate. The time sequences are also searched for the cyclic decreases in X-ray flux that were found in previous data sets. In § 5 we discuss the consequences of the observations.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *X-Ray Data*

The X-ray data were obtained with the *RXTE* satellite using the Proportional Counter Array (PCA), which detects photons in the 2–30 keV range. A summary of the observations is presented in Table 1. A total of six time sequences were obtained, each approximately 27 hr in duration, which is near the expected rotation period of the star. Since a primary goal of the program was to determine the timescale of the long-term X-ray variations, the visits were spaced at progressively increasing time intervals, ranging from 1 week to 5 months.

The PCA data were reduced using standard procedures within the FTOOLS reduction package, as described on the *RXTE* project Cook Book Web site.[6] The PCA has been slowly aging over the years. In an effort to decelerate this process the project periodically rests detectors by turning them off. During our observations various combinations of the PCA proportional counter units (PCUs), typically three, were operating at any one time, and this reduced the effective total count rate from our target correspondingly. More importantly, the energy dependence of the background models for each of the detectors had diverged. In fact, on 2000 May 13, a month before our fifth visit, the propane layer peeled away from the PCU0 unit. This event increased the soft background level for that unit. A revised background model based on new calibrations of this unit was not available at the time of our reductions. Therefore, we reduced the net fluxes of our observations for each PCU separately, and the color information from PCU0 was ignored in our last two data sets. After the initial reductions, the source count rate was adjusted to mimic that expected from a full five-unit PCA, so that the values could be compared with fluxes obtained during the 1996 and 1998 observing programs.

2.2. *Optical Observations*

Our photometric observations of γ Cas were obtained over four observing seasons between 1997 September and 2001 February with the T3 0.4 m Automated Photometric Telescope at Fairborn Observatory in the Patagonia Mountains of southern Arizona. The APT uses a temperature-stabilized EMI 9924B bi-alkali photomultiplier tube to acquire data through Johnson *B* and *V* filters. The APT is programmed to measure stars in the following sequence,

TABLE 1
SUMMARY OF *RXTE* PCA OBSERVATIONS

Visit	HJD (−2,450,000)	Date (2000)	Duration (hr)	Count Rate (counts s^{-1})	Position of Minimum[a] (hr)
1.........	1562	Jan 18	27.16	55	0
2.........	1569	Jan 25	27.17	37	158.0
3.........	1587	Feb 12	27.7	44	589.0
4.........	1621	Mar 17	28.4	96	. . .
5.........	1721	Jun 25	26.7	58	3808.9
6.........	1882	Dec 3'1	26.4	95	. . .

[a] Time from the minimum measured in visit 1.

termed a group observation: *K*, sky, *C*, *V*, *C*, *V*, *C*, sky, *K*, where *K* is a check star, *C* is the comparison star, and *V* is the program star. We used HD 6210=HR 297 (*V* = 5.80, *B*−*V* = 0.58, F6 V) as the comparison star and HD 5395=HR 265 (*V* = 4.63, *B*−*V* = 0.96, G8 IIIb) as the check star for our observations of γ Cas. Typically, two or three group observations were acquired each clear night at intervals of 2–3 hr. In the fourth observing season (2000/2001), up to several dozen group observations were obtained on four nights of more extensive monitoring. To keep coincidence count corrections small for these bright targets, a roughly 3.8 mag neutral-density filter was used for all integrations during the second through the fourth observing seasons. Integration times were 10 s for the check star and γ Cas and 20 s for the comparison star and sky measurements. During the first observing season (1997/1998), a 4.8 mag neutral-density filter was used for γ Cas and a 1.2 mag filter for everything else. This complicated the reduction of the observations to differential magnitudes for the first season and led to a small zero-point offset relative to subsequent seasons (see below).

Three variable-minus-comparison and two check-minus-comparison differential magnitudes in each photometric band were computed for each group observation and then averaged to create group-mean differential magnitudes. The group means were corrected for differential extinction with nightly extinction coefficients, transformed to the Johnson system with yearly mean transformation coefficients, and treated as single observations thereafter. The external precision of the group means, based on standard deviations for pairs of constant stars, is typically ∼0.004 mag on good nights with this telescope. Group-mean differential magnitudes with internal standard deviations greater than 0.01 mag were discarded to filter observations taken in nonphotometric conditions. A total of 921 *B* and 927 *V* group-mean differential magnitudes for γ Cas were obtained over the four observing seasons.[7] Further details of telescope operations and data reduction procedures can be found in Henry (1995a, 1995b).

3. LONG-TERM VARIATIONS

3.1. *X-Rays*

The representative X-ray intensity at a given epoch is assumed to be characterized by the mean value of the X-ray

flux evaluated over the 27 hr rotation period of the star. This mean value was derived for each of the six time sequences in the present study as well as the two observations taken in 1996 and one taken in 1998. The results are presented in Table 1, which shows that the X-rays can vary by a factor of up to 3 in intensity.

A periodogram analysis was carried out on the nine sample dates, and solutions were found at 70.1 and 84.4 days (see Fig. 2). In both cases the light curve was nearly sinusoidal. While these plots support the view that the X-ray fluxes have a long-term periodicity, the number of samples is insufficient to make a compelling case that the X-ray variations are strictly periodic. In fact, in § 3.3, we will introduce optical evidence that these X-ray variations are cyclic with a still unknown mean timescale.

3.2. *Optical*

The time histories of the *B* and *V* intensities for all four APT observing seasons are shown in Figure 3, while a summary of the characteristics of these data is given in Table 2. In all cases these time histories show a pronounced sinusoidal variation. A periodogram analysis for each observing season shows a variable period, decreasing from 61 days for the 1997/1998 season to 54 days in the 1998/1999 season and then increasing thereafter, reaching 93 days for the 2000/2001 season (see Table 2).

In addition to the cyclic 55–93 day periodicities, there also appear to be significant changes in the average magnitude from one observing season to the next. Since the first season was obtained through different neutral-density filters than
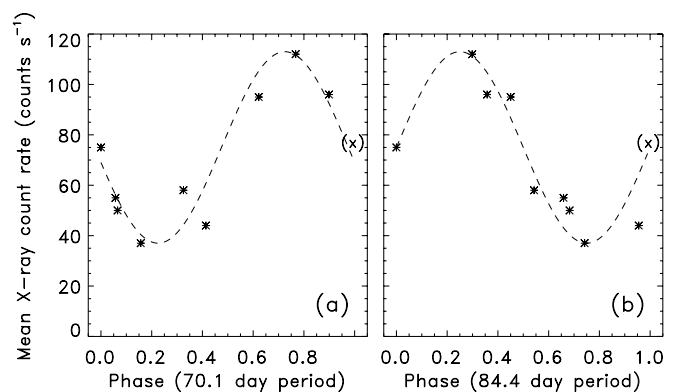

FIG. 2.—Median X-ray count rate for the nine observed times sequences (*asterisks*) as a function of cycle phase, assuming (*a*) a 70.1 day cycle period and (*b*) an 84.4 day period. The point at phase 0 has been replotted at phase 1 for reference. A sine wave (*dashed line*) has been included for reference.
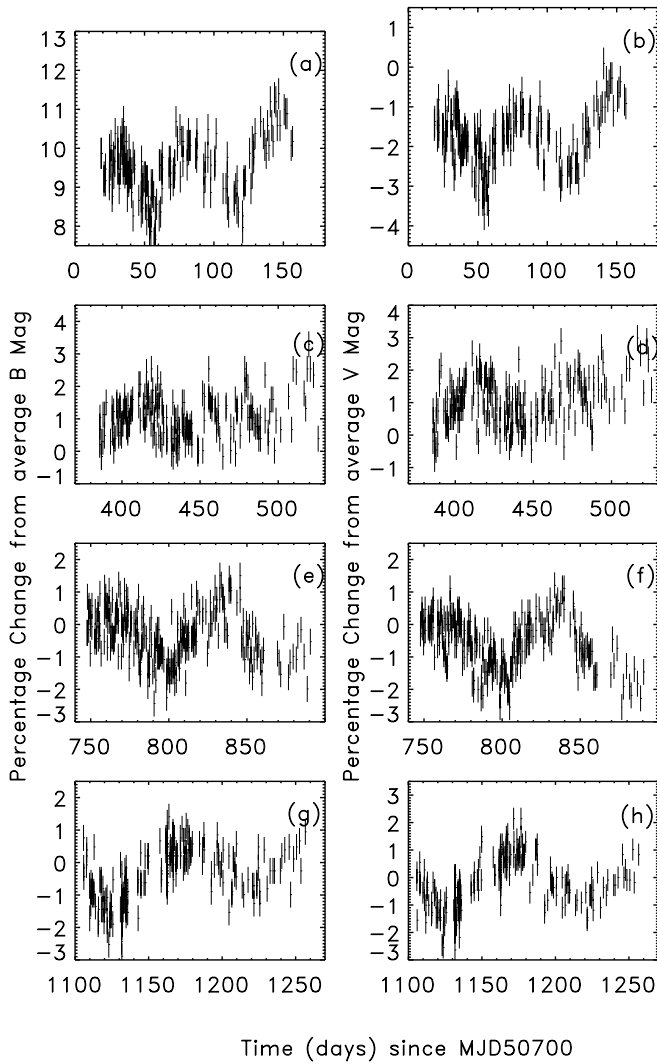
FIG. 3.—Summary of the optical B- and V-band observations for each of the observing seasons. B and V magnitudes have been converted to percentage deviation from the average magnitude derived over the entire data set.

the following observations, it is not possible to compare the optical fluxes of those data with later seasons. However, data for the last three seasons were obtained with identical instrumental configurations, so these long-term variations are probably real. Such variations are in fact typical of early-type classical Be stars (Pavlovski, Harmanec, & Bozic 1997; Moujtahid et al. 2000). Although the reason(s) for the variation is unknown, it is generally thought to be associated with an evolution of the disk structure (Hirata 1984).

In Figure 4 we examine the relation between the B and V fluxes during the four observing seasons. To facilitate the comparison, we have averaged all observations taken during an individual night and converted the fluxes to percentage deviation from the average intensity measured during that observing season. The dashed line in each plot represents the case in which the change in B equals the change in V, so there would be no color change associated with the change in intensity. The solid lines represent a linear least-squares fit of ΔB against ΔV. The slope of this fit is indicated on the plot. In all four observing seasons the slope is less than 1, indicating a greater fluctuation in V than in B. This result is consistent with other observed color variations. For

example, Horaguchi et al. (1994) show a strong positive correlation between the $(B-V)$ color and the V-band intensity of γ Cas, in which $(B-V)$ increased by 15% during a 45% increase in the V-band flux between 1960 and 1989.

To see whether the small slopes presented in Figure 4 are statistically significant, and not caused by the large uncertainties in the measured values of ΔB and ΔV, we repeated the analysis using 2 and 3 day averages. The results were nearly identical to those found for the 1 day averages. We also performed a statistical test in which we calculated the probability of obtaining the measured slopes from data in which the slope was actually equal to 1. To do this, we used a random number generator to create a set of 100 ΔB and ΔV samples with values ranging from $-1.5%$ to 1.5% and for which $\Delta B = \Delta V$. A second random number generator was used to add normally distributed uncertainties to the data. The distribution of uncertainties was centered on 0 and had a σ of 0.3%. A least-squares fit was then performed on the synthetic data set, and the slope was tabulated. Repeating the process 20,000 times, we were able to empirically establish the probability of obtaining any given slope. The probability distribution was Gaussian in shape and was centered at a slope of 0.9 with an FWHM of 0.1. The offset of the centroid slope from the expected value of 1.0 was caused by the large uncertainties in the values of the independent variable (ΔV). When these uncertainties were reduced in the simulation, the center of the probability distribution shifted to 1.0, as expected. From these simulations we find that the probability of measuring a slope of less than 0.8 is only 2.5%, while the probability of a slope less that 0.75 is only 0.07%. Thus, while the distribution obtained during the first season (Fig. 4a) is compatible with $\Delta B = \Delta V$, those obtained in other seasons are consistent with $\Delta B < \Delta V$.

To estimate the uncertainties in the slopes, we determined the rms deviation of the measured points from regression lines having slopes ranging from 0.3 to 1.5 and pivoting around the point $\Delta B = \Delta V = 0$. The derived distribution was a rather flat parabola centered at the slope deduced from the least-squares fit. The range of acceptable slopes was taken to be those values where the rms deviation was less than 1.5 times the minimum rms value. This range is indicated in Figure 4.

Future work by one of us (G. W. H.) will test these results further by extending the photometric monitoring into the near-IR.

3.3. *Comparing Optical and X-Ray Variations*

The sinusoidal shape and 75 day period found in the optical data during the 1999/2000 observing season are remarkably similar to the 70 day variations found for the X-ray fluxes (Fig. 2). An obvious question, therefore, is whether the variations in the two wavelength regimes are correlated. Unfortunately, it is not possible to compare the two data sets directly since only five of the nine X-ray time sequences have simultaneous optical coverage and most of those were obtained during the end of the optical observing season, where the uncertainties in the optical magnitudes were large.

An alternative approach is to determine an empirical model for the optical variations during the last two observing seasons and then compare the X-ray fluxes with the prediction of this model. We know from the period analysis

TABLE 2

SUMMARY OF OPTICAL OBSERVATIONS

Photometric Band	N_{obs}	Period (days)	Average Magnitude	Peak-to-Peak Amplitude (mag)
		Date Range (HJD −2,450,000): 0718–0856		
B..............................	177	60.8 ± 1.3	1.991	0.0142 ± 0.0012
V..............................	183	61.7 ± 0.3	2.163	0.0156 ± 0.0012
		Date Range (HJD −2,450,000): 1086–1225		
B..............................	207	52.8 ± 0.8	2.078	0.0086 ± 0.0012
V..............................	211	55.0 ± 0.9	2.132	0.0089 ± 0.0014
		Date Range (HJD −2,450,000): 1447–1590		
B..............................	247	72.2 ± 1.6	2.093	0.0154 ± 0.0012
V..............................	243	77.1 ± 1.8	2.150	0.0174 ± 0.0011
		Date Range (HJD −2,450,000): 1805–1956		
B..............................	290	93.2 ± 3.0	2.094	0.0172 ± 0.0010
V..............................	290	93.6 ± 2.8	2.146	0.0200 ± 0.0009

NOTE.—The individual Johnson BV photometric observations are available at http://schwab.tsuniv.edu/t3/gammacas/gammacas.html.
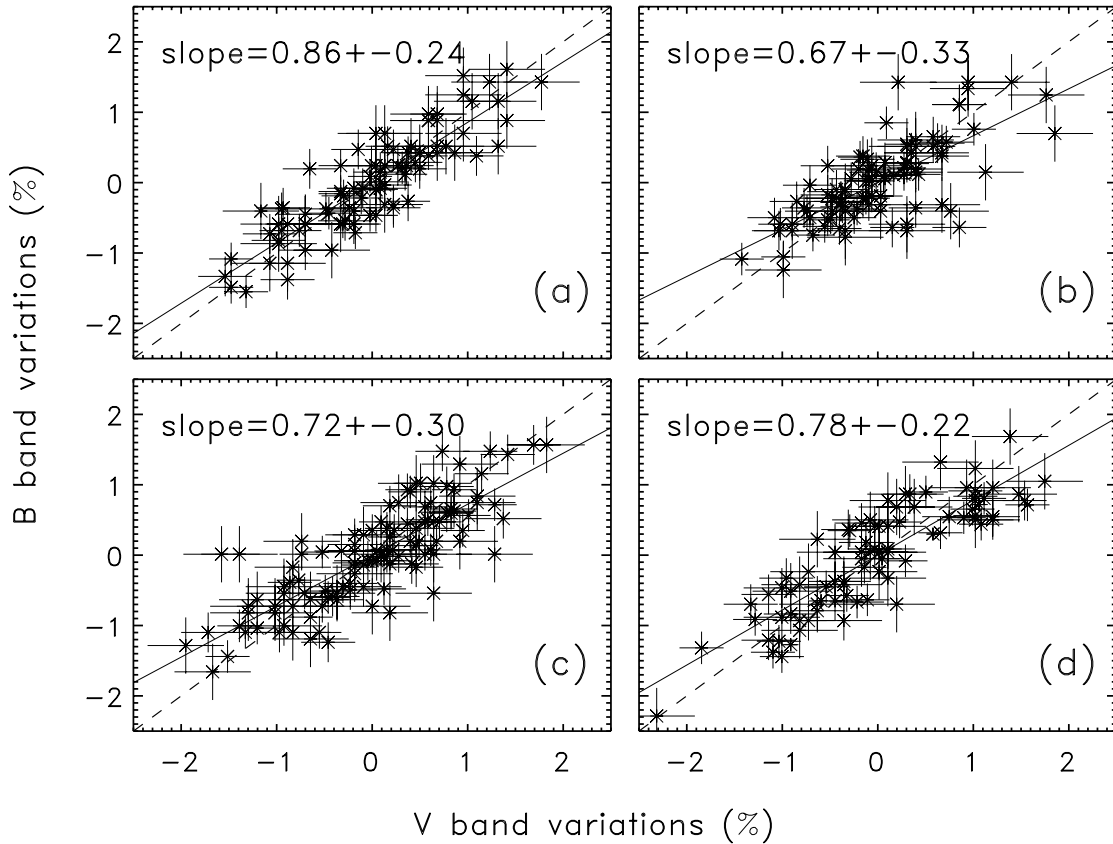

FIG. 4.—Comparing B- and V-band variations during each of the four APT observing seasons: (*a*) 1997/1998, (*b*) 1998/1999, (*c*) 1999/2000, and (*d*) 2000/2001. Points represent intensities averaged over 1 day intervals and expressed as a percentage deviation from the mean intensity for that observing season. The solid line is a linear least-squares fit to the data ("slope" indicates the proportionality factor between ΔB and ΔV), while the dashed line represents the case in which ΔB equals ΔV (no color changes).

discussed in § 3.2 that the 1999/2000 season has a period of roughly 75 days, while the 2000/2001 period was about 93 days. The optical variations were therefore modeled as a sine wave with a period linearly increasing with time. We also assumed a phase and mean intensity that varied linearly with time since the overall flux increased between the two seasons. Thus, the assumed light curve had the form

$$m_V = C_1(t) + D \sin\left[C_2(t) + \frac{2\pi t}{C_3(t)}\right],$$

where $C_i(t) = A_i + B_i t$ $(i = 1, 2, 3)$.

Here A_i, B_i, and D are all constants that were manually adjusted to fit the observations and t is the time (in days) from a reference date (HJD = 2, 451, 440). To increase the signal-to-noise ratio during the fitting process, the average B magnitudes were scaled to match the V magnitudes and the data were averaged into 3 day bins. The resulting fit is shown in Figure 5 and is remarkably good considering the crudeness of the model. The parameters of the fit were

$$C_2(t) = \text{phase} = 0.85\pi - 0.0015\pi t ,$$
$$C_3(t) = \text{period} = 65 + 0.027t \text{ days} .$$

Note that the period is 65 days at the start of the 1999/2000 season and increases to about 79 days at the end of the 2000/2001 season. This is somewhat shorter than was obtained when fitting the individual seasons with a sine curve. The difference is probably due to the relatively large change in phase during an observing season.

We next computed a numerical model for the X-ray light curve by using the values of period and phase that were found for the optical data and adjusting the average intensity (C_1) and the amplitude (D) to fit the observed X-ray fluxes. The results, shown in Figure 5b, exhibit a remarkably strong correlation between X-ray and optical fluxes. We note parenthetically that the year-to-year increase in the

optical data is not reflected in the X-ray fluxes. This is consistent with the fact that such variations are also commonplace in Be stars without strong X-ray emission (Pavlovski et al. 1997).

4. SHORT-TERM VARIATIONS

4.1. *General Properties of the X-Ray Flux*

In Figure 6 we show the X-ray variations for each of the six time sequences taken during the 2000 program. As discussed by SRC98 and RS00, the X-ray flux is composed of two components. The first consists of numerous short-duration bursts, termed shots, with lifetimes of ∼10 s to several minutes. These are superimposed on a background, or basal emission, that varies on timescales of 30 minutes to ∼10 hr. The basal emission can be thought of as the minimum flux at any given time. It was determined by two independent techniques (see RS00). Briefly, the first of these techniques relies on determining the median flux during time periods (of several minutes duration) when no significant shot events occur and then linearly interpolating between these samples. The second technique attempts to remove the shot events from the time sequence and then takes the average residual flux as the basal component. Both techniques produce similar results, although the second generally leads to a greater variability since groups of shots often merge into apparently longer term variations.

Our estimates of the basal fluxes are presented in Figure 6. Comparing the different time sequences shows that the character and timescale of the variations can change substantially from one visit to the next. However, some trends can also be detected within the data. For example, visits 1, 2, 3, and 5 are all taken during relatively low flux epochs, when the average count rate was 60 counts s^{-1} or less (see Table 1 and Fig. 5). In all cases these time sequences show a wide range of basal fluxes and a rather long timescale for the variations, similar to the behavior seen during the 1996 March observations (SRC98). In every case there was at some point a long-duration flux minimum (marked by a vertical line in Fig. 6), which will be discussed in more detail below. During visit 2, when the mean flux was low, there were times when the fluxes dipped to below 15 counts s^{-1} and the instantaneous X-ray output approached the normal levels for an early-type Be star. On one occasion the hardness ratio (formed from fluxes summed over 7.6–12 keV to the integrated 2–4.1 keV flux) also dropped significantly over several minutes to a new stable value. In contrast, the time sequences obtained during visits 4 and 6 were obtained during flux maxima, when the average *RXTE* fluxes were nearly 100 counts s^{-1}. The basal fluxes show much less variation for these epochs, and there is no indication of the broad flux minima.

Variations of the basal flux occur in all of the light curves and last from about 30 minutes to several hours. Details of several representative time sequences are shown in Figure 7. The timescales for these variations are much too small for them to be caused by rotational modulation, and their presence emphasizes the extremely dynamic nature of the X-ray source region. Short-duration events appear to be caused by dramatic increases in the production rate of individual shots. The longer term events often contain periods of several minutes or longer during which the shots temporarily disappear. The enhanced flux levels during this time there-
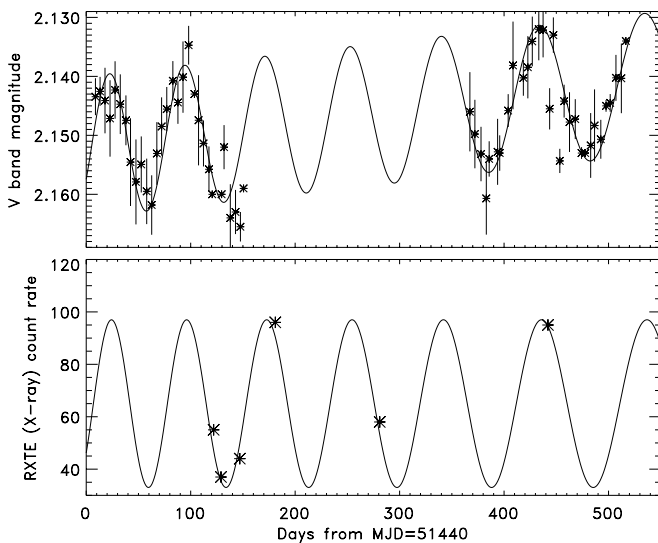

Fig. 5.—*Top*: 5 day averages of *V*-band magnitude over the 1999/2000 and 2000/2001 seasons. Error bars represent the rms variation of the data points. The solid line is an empirical fit to a sine wave with linearly increasing period and phase, as explained in the text. *Bottom*: Median *RXTE* count rates for the six time sequences obtained in 2000. The solid line is the sine wave model used in the optical fit, which has been adjusted in amplitude to fit the X–ray data.
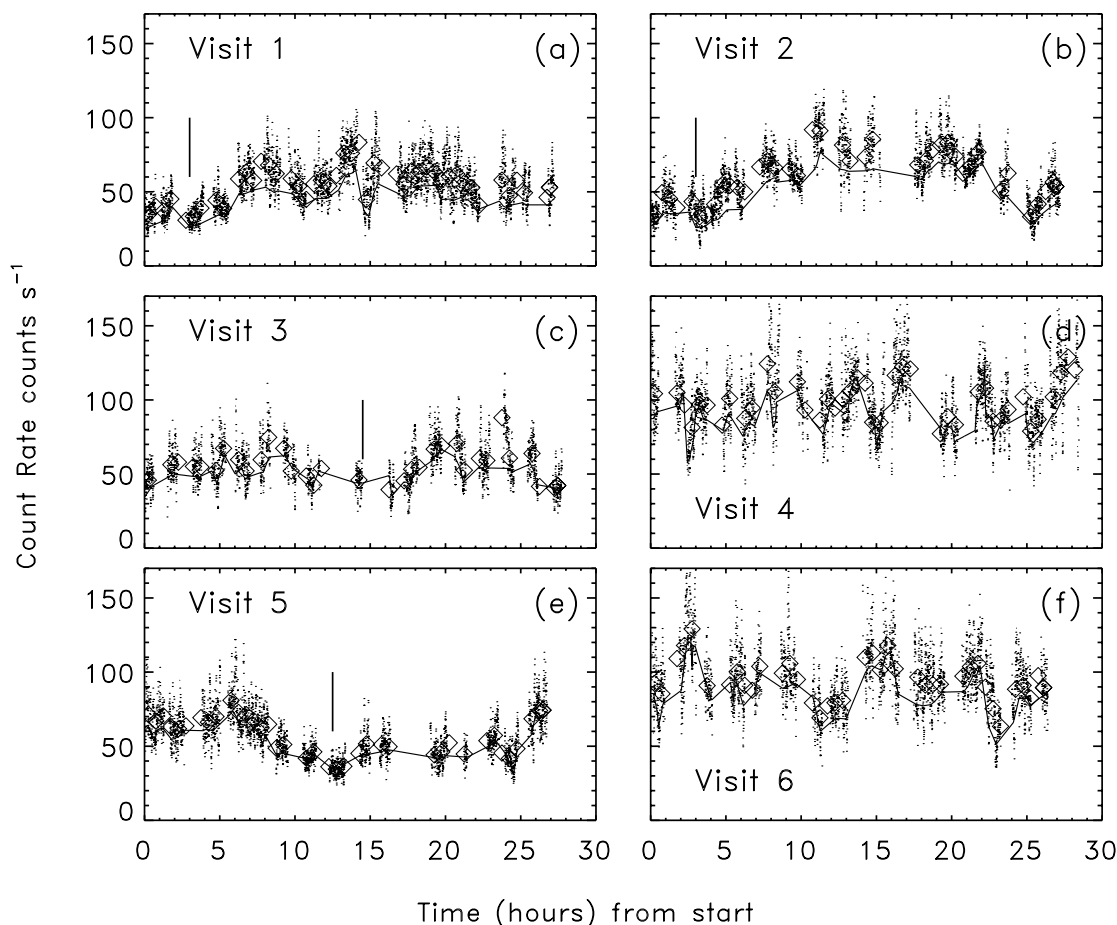
Fig. 6.—Summary of the six *RXTE* time sequences obtained in 2000. Points represent 16 s averages, diamonds are 30 minute averages, and the solid line represents estimates of the basal flux level. A vertical line in visits 1, 2, 3, and 5 shows the location of a flux minimum that was used to search for a rotation period of the star (see Fig. 8).

fore reflect a rapid evolution of the basal source region itself.

An inspection of the hardness ratios shows to first order that the hardness typically does not vary, even when the integrated net fluxes change by large factors. There are
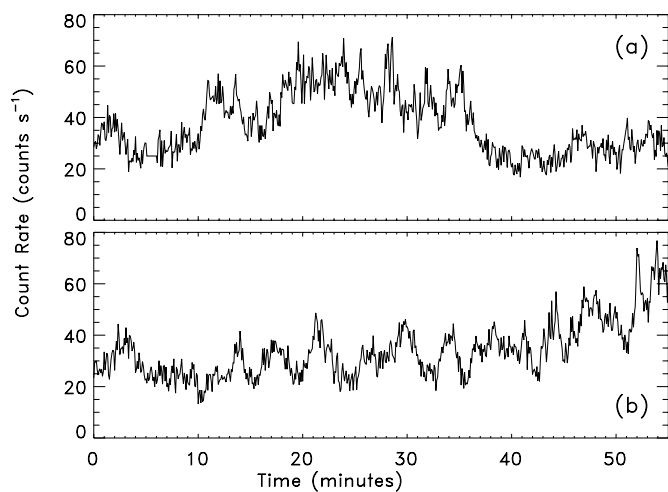

Fig. 7.—Detail of the *RXTE* time series at two representative times that shows both the short-term transients (shots) and the longer term variations in the underlying basal emission.

exceptions to this, and there is a statistically significant tendency for the hardness ratios to increase slightly when the net fluxes increase for several hours. There is also a striking case during visit 4 in which the hardnesses decreased from an abnormally high value to normal in 20 minutes. These results are in accord with our analysis of the 1996 and 1998 data sets (see SRC98, RS00).

4.2. *Redetermining the Rotation Period*

The broad flux minima seen in visits 1, 2, 3, and 5 are very similar to a feature seen during the 1996 March observations (see SRC98). The duration for this feature is about 7 hr and may therefore be caused by the rotational modulation of a structure on or near the surface of the star, reminiscent of a solar coronal hole. The shape of the time series for this feature appears to be stable for moderately long periods of time, as shown in Figure 8. In this plot we compare 30 minute averages of the time sequences obtained during visits 1 and 3 and assume a 27 hr rotation period. The light curve for visit 3 has been shifted so that the flux minimum matches the minimum seen during visit 1. Comparisons between other time sequences that have the feature show a similar agreement. The stability of the feature suggests that it is formed in a relatively long lived structure (the feature may simply be masked by enhanced activity from other longitudes on the star during the two visits where it was not appa-
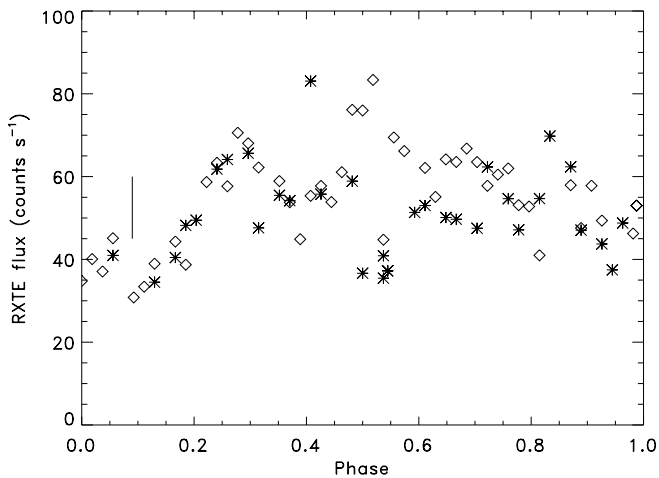
Fig. 8.—Comparing the 30 minute average X-ray fluxes obtained during visit 1 (*diamonds*) with average fluxes obtained during visit 3 (*asterisks*). The points are plotted as a function of rotation phase assuming a 27 hr period. The fluxes from visit 3 have been shifted in phase to align the flux minimum feature seen at phase 0.1.

rent) and can therefore be used as a marker from which a rotational period could be deduced. Such markers were used by SRC98, who used the feature in the 1996 March *RXTE* data together with *ASCA* satellite data taken 11 days earlier to determine a rotation rate of 1.125 days (27 hr). This is very similar to the period of 1.12277 days derived from UV variations (RS00).

The relative times at the center of the flux minimum for each of the relevant time sequences are given in Table 1; these are referred to as the first sequence in 2000 January. However, a simple period analysis shows that there is no unique rotation period that can account for all of these time intervals. This implies that the feature is either dissipating and reforming at new longitudes or is drifting in longitude (ϕ) at a rate that changes with time, so that the longitude at any given moment is given by

$$\phi(t) = \phi(0) + Ct^\beta .$$

If β were equal to 1, so that the drift rate were a constant, then the markers would still be periodic except that the measured period would differ from a true rotation period. Using the measured time intervals from Table 1, we find that a suitable set of parameters is given by apparent rotation period at $t_0 = 25.18$ hr, $C = 0°.241$ hr^{-1}, and $\beta = 1.2$.

We stress that these figures refer only to this set of X-ray data and should not necessarily be preferred over those fits to earlier data since we expect that the values of C and β would vary with time.

4.3. *A Search for Periodic Decreases in the X-Ray Flux*

In their analysis of the 54 hr X-ray time sequence obtained in 1998 November, RS00 discovered the presence of cyclic decreases ("lulls") in the X-ray flux that occurred every $\approx$7.5 hr. These decreases were also found in the 1996 March observations. To check for a persistence of the X-ray lull pattern, we carried out the same analysis on the six data strings obtained in 2000. Surprisingly, with the possible exception of time sequence 5, no evidence for lulls with this period was found in the data, as shown in Figure 9. In Figure 9a the autocorrelation analysis of the 1998 November

sequence is shown for reference. Light curves obtained during low-flux epochs (visits 1–3) showed no indication of periodic lulls. However, some evidence of cyclicity was seen during the high-flux visits, but on a much shorter timescale, i.e., 3.5 hr for visit 4 (Fig. 9b) and 5.8 hr for visit 6 (Fig. 9d). The general indication is that the lull cycles can develop, last for several months or more, and then disappear. Lull cycles from these different "episodes" apparently do not have to take on a special value (like 7 hr), as had been tentatively concluded in RS00. We are as yet no closer to a fundamental understanding of this peculiar phenomenon.

4.4. *Short-Term Variations in the Optical Flux*

Most of the APT observations consisted of only one or two samples per night. However, on four nights during the 2000/2001 observing season more intensive observations were carried out, covering 4 hr when the source was near the zenith. The resulting light curves are shown in Figure 10. Despite the large scatter, it is apparent that there are real variations on the 1%–3% level that have timescales of several hours (see especially Fig. 10c). X-ray variations can also occur on these timescales (see, e.g., Fig. 1b). Unfortunately, none of the extended optical data sets were taken precisely during an *RXTE* visit, so the short-term X-ray/optical association cannot be examined in detail.

4.5. *Hα Variability*

During 1928–1934 and from 1969 to the present the Hα profile of γ Cas has been dominated by cyclic variations of the V/R emission ratio (see, e.g., Doazan et al. 1983). These variations are now widely believed to be due to a dynamical instability in the disk that excites a one-armed density wave that precesses around the star on a timescale of 5–7 yr. This feature has been imaged interferometrically in Hα light and has been shown to rotate around the star on this timescale (Berio et al. 1999). During the year 2000 the V/R ratio decreased from a value of about 1.3 to 1.0 (G. J. Peters 2001, private communication). During this time the equivalent width (EW) of the line also decreased by about 3%, continuing a slow downward trend since its gradual ascent to maximum in 1994.[8]

The original impetus of our 2000 *RXTE* program was to measure a timescale for X-ray changes in order to determine whether the epochal X-ray flux levels were related to the passage of the one-armed circumstellar feature. This might occur if, for example, the density of the arm affected an interaction between a putative stellar magnetic field and a magnetic field entrained or self-generated in the disk. We can now say (see Fig. 5) that there is no evidence for a year-to-year trend in the X-ray flux that could be ascribed to a disk arm precession cycle.

The discovery of the cyclic variability in the optical continuum leads to the question of whether this cycle is also present in the Hα data. To help us address this question, K. Bjorkman and A. Miroshnichenko kindly put at our disposal a series of 88 Hα line profile observations obtained at the Ritter Observatory during an 18 month period from late 1999 to early 2001. Measurement of these data shows that there are no apparent cyclic variations in the Hα EWs on

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[8] See the article by E. Pollman in the Be Star Newsletter, Volume 35, available at http://www.limber.org/benews/volume35/pollmann/take6/pol0.html.
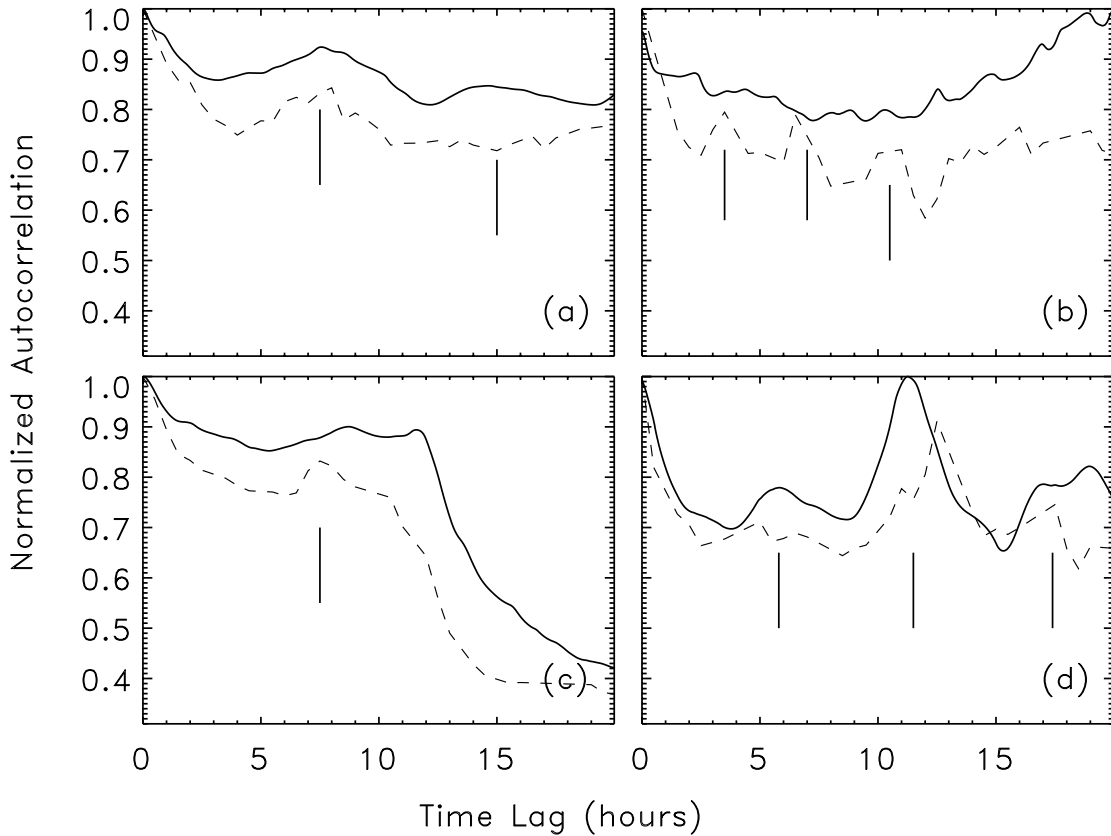
Fig. 9.—Autocorrelation functions for the reciprocal X-ray flux obtained from various time sequences: (*a*) 1998 November, (*b*) visit 4 (2000 March 17), (*c*) visit 5 (2000 June 25), and (*d*) visit 6 (2000 December 3). The solid line is a calculation obtained from the basal flux measurements, while the dashed line is the same calculation using 30 minute average fluxes (which include the effects of shots). Vertical lines indicate equally spaced peaks in the correlation that point to periodic behavior. The indicated periods are (*a*) 7.5 hr, (*b*) 3.5 hr, (*c*) ∼7 hr, and (*d*) 5.8 hr.

any timescale, including one near 70 days. The same holds for the shape of the normalized profile, which shows only a steady, long-term decrease in the amplitude of the violet peak. However, we note that EWs are defined with reference to the continuum flux. Therefore, the Hα *fluxes* should actually have a variation that is similar to that of the optical continuum, provided cyclic EW variations were not lost in the noise. To test whether 3% EW variations were actually detectable in these data, we added synthetic sine curves with a 3% amplitude and then analyzed them with a periodogram tool, PDM, in *IRAF*. The calculation was then repeated with the sine curve starting at different phases. For each of these trials, we were able to detect the input signal at about the same, 2 σ, level. This implies that an *absence* of a modulation in the Hα fluxes, seen as a reflex in the EW data, can be verified. This is a nontrivial point. Since the disk is certainly optically thick in Hα and thin in the continuum, the two could conceivably show different responses.

5. DISCUSSION

5.1. *Examining the Binary Accretion Hypothesis*

As mentioned in § 1, it is commonly suggested that the X-rays from γ Cas originate from mass infall onto a degenerate companion. For years this hypothesis could not be directly tested because no evidence for a companion existed. However, recently Harmanec et al. (2000) have reported, on the basis of periodic velocity variations in the Hα and He I

lines, that γ Cas is likely to be a binary. Their solution for the velocity curve shows that it is in a moderately eccentric orbit with a period of 203.59 days and that its companion has a mass ∼0.5–2 $M_\odot$. The component stars in such a system would be separated by about 0.8 AU.

Standard Bondi-Hoyle accretion theory (Bondi & Hoyle 1944) suggests that the X-ray luminosity from an accreting degenerate companion will vary as $\rho V_{\rm rel}^{-3}$, where ρ is the local density and $V_{\rm rel}$ is the relative velocity between the star and the accreting gas. Since these properties vary with orbital phase, comparing the observed *RXTE* X-ray flux with expected variations based on the orbital ephemeris provides a clear test of the degenerate companion model. This comparison is done in Figure 11. Here the expected X-ray flux was calculated using the formalism for wind accretion onto a degenerate star described by Waters et al. (1989), in conjunction with the Harmanec et al. (2000) orbital ephemeris with $e = 0.26$. In this calculation it is assumed that the density varies as r^{-2} and that the wind has reached its terminal velocity (∼1800 km s^{-1}), so that $V_{\rm rel}$ does not vary with orbital phase. Even stronger phase variations are expected if the companion is embedded in the stellar Keplerian disk since the density there varies as r^{-n}, with $n = 3.3$–4.5 (Waters et al. 1991). In clear contrast to the results presented in Figure 2, Figure 11 shows that the 1996–2000 *RXTE* observations have a random scatter when folded over the Harmanec et al. (2000) binary period. We believe that this result argues strongly against the idea that the X-rays originate from the companion.
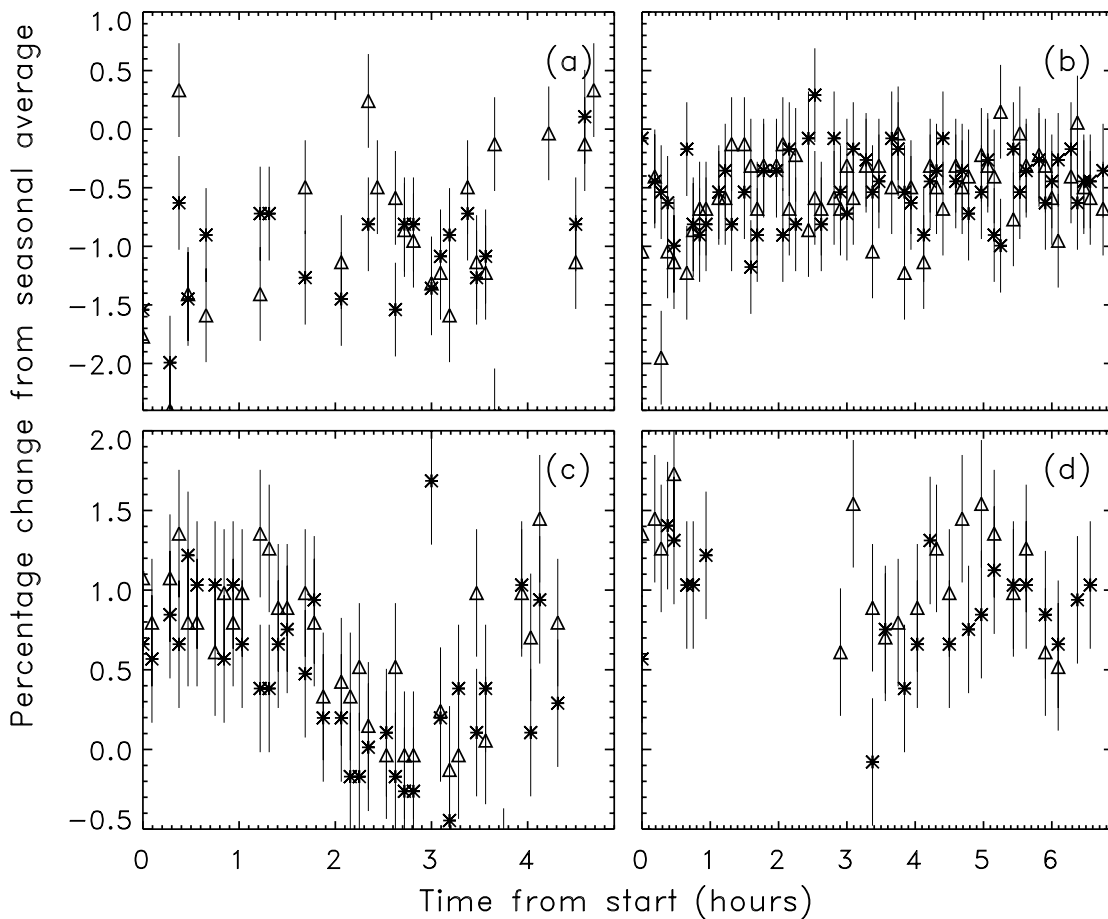
FIG. 10.—Short-term optical variations obtained during the 2000/2001 observing season. Fluxes are represented as the percentage change from the mean magnitude seen during that observing season. Triangles represent *V*-band observations, while asterisks mark *B*-band data. Observing dates are (*a*) 2000 October 14, (*b*) 2000 October 17, (*c*) 2000 November 14, and (*d*) 2000 November 18.

Recently, A. Mironishenko & K. Bjorkman (2002, private communication) have used new data to confirm the Harmanec et al. (2000) orbital period but suggest that the ellipticity may be small. If this turns out to be the case, then

FIG. 11.—Mean *RXTE* fluxes folded to the Harmanec et al. (2000) period of 203.59 days. Their ephemerides are applied to Bondi-Hoyle accretion theory (with scaling factor adjusted to mean of observed fluxes) to produce the dashed curve, which clearly does not fit the data.

the X-ray variations predicted in Figure 11 would disappear. In this scenario, variable X-ray emission from a companion would require changes in the wind mass-loss rate or velocity. While this is conceivable, it is unclear how or where these wind changes would originate. If the companion were embedded in the disk, then the orbit is likely to have at least a small inclination to the plane of the disk (see, e.g., Waters et al. 1989). Since Be disks are thin, the star would then be subject to substantial phase-related density and relative velocity variations, with consequent phase-related X-ray production, even for a circular orbit.

The current study provides two additional pieces of evidence against the companion as the source of the X-rays. The first involves the simple fact that the periods of both the optical and X-ray variations *change with time*, contrary to the behavior expected from a stellar companion. The second concerns the strong correlation between the X-ray and optical changes (§ 3.3). Even if we assumed that the Harmanec et al. (2000) analysis was erroneous and that the star had a companion with a 70 day period, an X-ray source at that distance would be unable to substantially affect the Be star's optical flux through irradiation. In fact, known high-mass X-ray binary systems with periods near 70 days and X-ray fluxes that are 2–4 orders of magnitude larger than those seen in γ Cas are not associated with any correlated optical
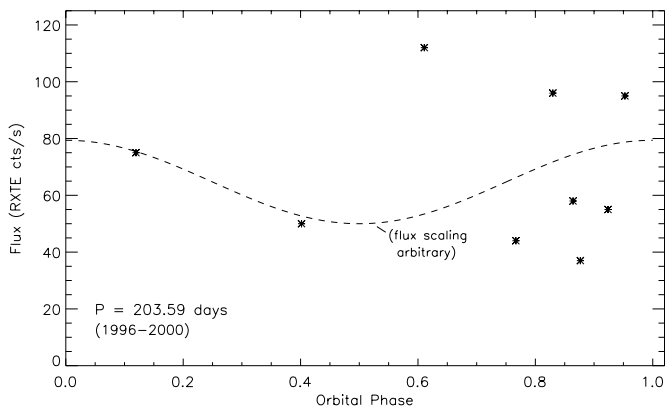
variations (Liu, van Paradijs, & van den Heuvel 2000). The idea that the optical variations are caused by reprocessing of the X-ray photons is also contradicted by energy considerations, as shown in § 5.2.

Another possibility is that the X-ray flux variations from a mass-accreting degenerate companion are driven by density changes associated with the optical variability (e.g., changes in the inner disk structure; see § 5.2). In this case, the changing periods and close correlation of fluxes could conceivably be explained provided that the companion was embedded within the disk and that the disturbance propagates rapidly from the site of the optical emission near the Be star to the companion. Disturbances can propagate rapidly (at the Alfvén velocity) but only along the magnetic field direction, which is primarily azimuthal within the disk (see § 5.3). Radially directed disturbances will propagate near the local sound speed, c_s. For example, in the dynamo discussed in § 5.3 the relevant velocity is αc_s (E. Vishniac 2002, private communication), where α is the effective viscosity and is probably less than 1 for Be stars (Okazaki 2001). Assuming a mean disk temperature of $T = 10^4$ K, one finds $c_s \approx 13$ km s^{-1}. Thus, for a system with a separation of 0.8 AU, there would be a phase lag of about 100 days between the optical and X-ray light curves.

5.2. The Site of Optical Variations

The strong correlation between the X-ray and optical variations suggests a common origin. It is tempting to postulate that the optical variations arise from the reprocessing of the X-ray photons as they impinge the stellar photosphere. However, simple energetic considerations show that this is not tenable. The bolometric luminosity of γ Cas is about 10^{38} ergs s^{-1} (see, e.g., Harmanec 2000), and the epochal average X-ray flux according to our RXTE data is in the range $(0.4–1.1) \times 10^{33}$ ergs s^{-1}. Thus, a 3% variation of the bolometric flux corresponds to an energy input of more than 10^3 times the observed X-ray energy. Using a Kurucz theoretical LTE spectrum of a star with an effective temperature of 27,000 K and $\log g = 4$, we find that the flux contained in the B band and longer wavelengths equals $\sim 4.3\%$ of the bolometric flux. Thus, even if the 3% optical variations are restricted to the B and V bands, they still involve energies that are 100 times those observed in the X-rays.

If the optical variations are not produced directly by the X-rays, then it is likely that the two are driven by the same engine. One possibility is that the optical variations come from the surface of γ Cas. In SRC98 we proposed a model in which the X-rays were produced by electron beams directed toward the star. These beams impulsively heat the stellar photosphere (at densities of 10^{13}–10^{14} cm^{-3}) to temperatures near 10^8 K and produce the shots. The heated material expands rapidly into the overlying magnetic canopy, where it radiates slowly and is responsible for the basal flux (see RS00 for more details). In previous studies we have assumed that all of the beam energy goes into the X-ray–emitting plasma. However, it is possible that a significant amount may also heat the stellar photosphere to more moderate temperatures. In addition, the physical processes that result in the electron beams (see, e.g., Smith & Robinson 1999) may also produce high-energy protons, conduction fronts, and/or Alfvén waves (see, e.g., Ulmschneider, Priest, & Rosner 1991), all of which could heat the stellar atmosphere and account for the optical variations.

One problem with this general scenario is that a heating of the stellar atmosphere necessarily results in a decrease in the $(B-V)$ color of the star. This is contrary to the observations presented in § 3.2, which show an *increase* in $(B-V)$ with increasing luminosity during the ~ 70 day cycle. A heating also implies that the optical variations should be correlated with greater variations in the ultraviolet. To check this, we have compared the UV continuum fluxes extracted from 14 available high-dispersion large-aperture, LWP camera observations from the IUE data archive at MAST.[9] These fluxes show no credible periodic variations in the near-UV to $\pm 2\%$. A similar exercise for 164 large-aperture SWP camera observations shows no reliable variations of the rotation-averaged far-UV intensity with amplitude greater than about 0.5%. Thus, it appears unlikely that the optical flux modulations originate from the stellar surface.

An alternative possibility is that the optical variations arise within the circumstellar disk. This is a commonly invoked explanation for other long-term optical variations seen in Be stars (see, e.g., Hirata 1984). For example, Horaguchi et al. (1994) document a tight correlation between enhanced V-band flux and increased $(B-V)$ color of γ Cas during the disk-building phase that occurred between 1960 and 1990. The relationship between B and V reported by Horaguchi et al. is also similar to the results presented in § 3.2, i.e., $\Delta B/\Delta V = 0.76 \pm 0.08$ (Fig. 4). To understand this behavior, we note that the disk, which has a density-averaged temperature of about 10,000 K (Millar, Sigut, & Marlborough 2000), exhibits a progressively increasing contribution to the observed flux with increasing wavelength. It contributes some 0.05% at 1900 Å (Ph. Stee 2001, private communication), a few percent near 4800 Å, about 20% near 6500 Å (Stee & Bittar 2001; Horaguchi et al. 1994), and virtually 100% above 2 μm (Waters et al. 2000). Thus, variations in the disk brightness would naturally explain both the increase in $(B-V)$ color with increasing optical flux and the lack of substantial UV variations. However, it should be pointed out that the observed flux variations are probably not simply the result of mechanical heating through, for example, resistive dissipation of disk turbulence. Assuming a Keplerian disk of mass $\sim 10^{-9}$ $M_\odot$ (Waters et al. 2000), one finds that the total orbital kinetic energy of the disk is only $\sim 10^{38}$ ergs. Thus, the disk does not appear to have enough reserved energy to allow it to power changes in radiative flux, amounting to 10^{35}–10^{36} ergs s^{-1}, for more than several minutes. Instead, we assert that the observed energy most likely comes from the stellar radiation field, with the physical processes in the disk simply modulating the amount of energy that is absorbed and released by changing the optical thickness of the disk. This idea will be discussed in more detail in § 5.3.

In our picture the X-ray emission from γ Cas comes from energy stored within unstable magnetic fields. Long-term changes in the X-ray emission should therefore reflect long-term changes in the magnetic fields. This suggests in turn that the X-ray emission is being driven by a magnetic dynamo. The close agreement between the X-ray and optical variations implies that this dynamo is also the controlling mechanism for the optical variations. The physical

processes explaining how this might happen are discussed in the following section.

5.3. *A Possible Dynamo*

Smith & Robinson (1999) suggested that many of the observed X-ray and UV characteristics of γ Cas could be explained by the dynamical interactions between putative magnetic fields on the star and its disk. While the short-term variations in the basal flux and burst rate (§ 4.1) can be attributed to an inhomogeneous magnetic structure, the long-term variations (§ 3) are most likely caused by cyclic changes in the magnetic field strength and/or area coverage on the star or within the disk. We believe that this implies the presence of a magnetic dynamo, as mentioned above, and can think of no other explanation that fits our observations. The site of this dynamo is uncertain. It may occur on the Be star itself. Such a dynamo would be completely different from that operating on late-type stars such as the Sun since a conventional α-Ω dynamo requires convective motions, which are not present on γ Cas. It is possible that Coriolis forces on this rapidly rotating star may substitute for the convection, as suggested by Airapetian (2000). However, the fact remains that γ Cas is currently the only known Be star that shows these types of X-ray and optical variations, and there is nothing particularly unusual about the star itself other than its not atypical Be character.

The alternative is that the dynamo operates in the circumstellar disk, which is among the densest of all known Be stars (Poeckert & Marlborough 1978; Lamers & Waters 1987; Telting 2000). As described in Balbus & Hawley (1998), a disk dynamo is substantially different from a classical stellar dynamo. In a star, the convective turbulence that is responsible for amplification of an existing seed field (the so-called dynamo α-effect, not to be confused with the Shakura-Sunyaev viscosity α, both used in disk accretion studies) is a global stellar property. These motions contain much more energy than the magnetic fields and are therefore unaffected by the growth in the field strength. In a disk, however, the turbulence is produced by the interaction of a seed field (presumably coming from the star) and the Keplerian shear within the disk through the magnetorotational instability of Balbus & Hawley (1991), which is expected to operate to some extent whenever a magnetic field is embedded in a Keplerian disk (Balbus & Hawley 1998). The result is an interacting system in which turbulence amplifies the magnetic field, which, in turn, increases the level of turbulence. Numerical simulations have shown that such a mechanism can produce a self-sustaining dynamo in either cyclic or chaotic forms. The form of the dynamo depends on such physical characteristics as the strength and configuration of the background magnetic field, the density structure of the disk, and the conditions at the edge of the disk (see, e.g., Torkelsson & Brandenburg 1994; Brandenburg et al. 1995; Hawley, Gammie, & Balbus 1996). Of particular interest to our study are numerical simulations of Brandenburg et al. (1996), which predict a cyclic dynamo with a period of $\sim$30 times the Keplerian rotation period. If this simulation is applicable to γ Cas, then the observed 70 day cycle implies that the dynamo is operating in the inner disk, at a radius of about 2.5 R_* (assuming $M_* = 17\ M_\odot$ and $R_* = 7\ R_\odot$). This is just slightly outside the Keplerian corotation radius, $R_K = 1.7\ R_*$, and is near the location where the disk density seems to be highest (Berio et al. 1999).

We suggest that the observed optical variations in γ Cas are caused by the turbulence generated by the disk dynamo and the effect of that turbulence on the density structure of the disk. To understand this process, we note that the primary source of energy within the disk, including that which powers the optical emissions, is the radiation field of the star. Since the disk is optically thin in the continuum (see, e.g., Stee & Bittar 2001), the amount of radiation that is absorbed and reemitted is dependent on the local emission measure, $\int n_e^2\, dV$. Thus, changes in the density will be reflected as variations in disk brightness. Since the disk is moderately stable over a timescale of years, we stipulate that in the absence of a dynamo there exists a dynamic equilibrium involving the wind, magnetic fields, turbulence, viscosity, etc., that will determine the density structure. As discussed extensively by Balbus & Hawley (1998), the introduction of magnetic turbulence into the disk will result in the outward transfer of angular momentum. This causes a net inward drift of material and a consequent increase in the density of the inner disk, which then increases in brightness. As the magnetic fields decrease later in the dynamo cycle, the turbulence will also decrease, so the disk will evolve back to its original density and brightness.

The energy source for dynamos operating in stellar *accretion disks* is ultimately the gravitational energy of the accreted material. In contrast, we propose that the dynamo within the *decretion* disk around γ Cas operates just above the Keplerian corotation radius R_K and is supplied with energy by magnetic fields that connect the disk to the stellar surface. To see why this is necessary, consider that material inside R_K must rotate faster than the stellar surface in order to maintain its distance from the star. *In the absence of other processes*, we expect that magnetic fields tied to the stellar surface will produce a drag on this material and cause it to spiral onto the star, resulting in an inner edge to the disk that is at or near R_K. Above R_K, these same fields will impart energy and angular momentum to the gas from the star's rotational reservoir. This action prevents the matter within this region from being lost during the maximum of the dynamo cycle. In this context we note that Berio et al. (1999) find evidence for a density maximum at a radius of about 2.5 R_*. Further, Smith & Robinson (1999) report on drifting spectral features near the Si IV resonance lines that can be interpreted as corotating clouds near 2.5 R_*. This provides evidence for the existence of surface-connected magnetic fields at these heights. More evidence comes from Waters et al. (2000), who found that the hydrogen Pfund, Humphreys, Hansen-Strong, lower level 8 and lower level 9 emission-line series in the infrared spectrum of γ Cas all increase in width with decreasing line strength, as expected in a disk where the rotational velocity decreases with height. The maximum width of the lines in these series is in the range 500–650 km s^{-1}. From the stellar parameters we have adopted, and assuming an inclination of 46° of the rotational axis to our line of sight (Quirrenbach et al. 1997), we estimate that the $v \sin i$ of a Keplerian disk at the surface of the star is only $\sim$480 km s^{-1}. Thus, even acknowledging possible errors in our assumed parameters, the large line widths suggest that the inner part of the disk is being forced to corotate with the stellar surface, presumably through the action of interconnecting magnetic fields. If this is true, then adopting a $v \sin i$ of 230–310 km s^{-1} for the star (see, e.g., Slettebak 1982) implies that the forced corotation extends to a height of about 1.6–2.8 R_*, i.e., near or just above R_K.

6. CONCLUSIONS

In this paper we have described the results of monitoring γ Cas at both optical and X-ray wavelengths. The graduated spacings in the *RXTE* PCA observations have succeeded in defining a timescale for long-term X-ray variations whose existence was merely indicated from previous random shorter term monitorings. The sequence of rotation-averaged X-ray fluxes conflicts with both the period and amplitude of the modulation expected from conventional Bondi-Hoyle accretion onto the newly discovered binary companion. Since this is the same theory used to predict the X-ray flux level from γ Cas in binary models (see, e.g., Kubo et al. 1998), this disagreement poses manifest problems for the binary accretion hypothesis.

The individual X-ray light curves also show "features" that indicate the presence of evolving active centers. Comparison of light curves shows that these structures evolve in time and probably migrate across the stellar surface. Thus, using the X-ray signatures as markers is not a reliable method for determining the star's true rotation period. It is unclear whether this conclusion affects our earlier determination of the period, mainly from UV markers.

Probably the most surprising result of the study was the discovery of cyclic variations in both the X-rays and optical fluxes. A study of these variations shows that

1. the X-rays and optical fluxes appear to have a strong positive correlation,
2. the cycle length changes with time, with observed values ranging from 55 to 93 days, and
3. the amplitude of the optical variations is greater in the *V* than the *B* band.

In previous papers of this series we have suggested that the X-rays from γ Cas arise from plasma heated by magnetic instabilities and stresses. The results of the current work indirectly confirm this hypothesis by providing evidence against the binary star hypothesis, which appears to be the only other viable alternative capable of explaining observed X-ray fluxes and temperatures.

The short timescales of X-ray flares (often as short as a few seconds; SRC98) imply that this emission is formed in a relatively high density region, probably the upper photosphere. The location of the basal X-ray component is somewhat more uncertain, although there are indications that it is also produced near the star. However, the properties of the optical variability, particularly the increase in $(B-V)$ color with increasing flux and the lack of correlated changes in the UV flux, suggest that these are generated within the Be disk and not from a change in photospheric flux. The optical fluctuations contain far too much energy to be caused by the reprocessing of X-rays. In view of this fact we suggest that the correlated X-ray and optical variations both are driven by a cyclical process, which we conjecture is due to a magnetic dynamo and probably operates within the disk. Such a dynamo would provide a time-modulated mean magnetic field in the disk that drives X-ray activity and is also associated with the production of magnetic turbulence through the Balbus-Hawley instability. This turbulence influences the transport of angular momentum within the disk and will influence the density structure, and therefore the brightness, of the disk. Thus, the control of the X-ray and optical variations arises from two separate but related properties of the dynamo. The study of disk dynamos is still

in its infancy. Most studies to date have been specific to accretion disks rather than the decretion disk of Be stars such as γ Cas. However, at least some ab initio calculations, while specific to special conditions, do show that cyclic disk dynamos are possible and can vary on a timescale comparable to that reported here. Thus, the idea of a disk dynamo on γ Cas should be pursued.

At this point it is worthwhile summarizing the "big picture" emerging from the series of papers starting with SRC98 concerning the production of anomalous X-rays in γ Cas. In this picture a highly complex magnetic topology exists on the surface of the star. These fields evolve rapidly and may also migrate across the stellar surface. During times of low X-ray flux the fields appear to be concentrated into two or three complexes. However, when the X-rays are near maximum the fields are more evenly spread across the disk, and the X-ray flux shows a smaller rotational modulation. A key assumption in our picture is that the star's magnetic field becomes entrained in the inner part of the ionized, circumstellar disk. This interaction has two consequences. First, the stellar magnetic field causes the production of turbulence within the disk through the Balbus-Hawley instability. This turbulence amplifies and modulates the stellar "seed" field through a disk dynamo. The turbulence also affects the density structure of the inner disk, causing the disk brightness to change. Second, the difference in angular rates of rotation between the star and disk results in the stressing and shearing of the magnetic lines of force. This causes the ejection of high-velocity plasmoids (similar to solar "coronal mass ejections"; Smith & Robinson 1999) as well as the generation of high-energy particle beams, some of which are directed toward particular regions on the star. The impact of these beams on the surface results in explosive heating of the ambient plasma to a temperature near 10^8 K, resulting in the X-ray shots. The rapid expansion and entrapment of this plasma along overlying magnetic field lines result in the longer lived basal X-ray emission, which usually accounts for most of the X-ray flux we observe. Clouds of translucent material also form in these same magnetic complexes and are responsible for periodic absorptions in the ultraviolet continuum flux. The ionization state of particles in various parcels of the star's radiative wind is also modulated as they "see" these X-ray–generating centers (Cranmer et al. 2000). Altogether, the disk serves as a conduit in which the star's rotational energy is converted to a time-dependent magnetic field and turbulence. The field is dissipated, in part, by the ejection of plasmoids and particle beams. Note that the optical variations are initiated by the motions set up by the dynamo but are not strictly powered by it.

What are the implications of this picture for this and other stars observed over a period of time? We do not really know whether the production of X-rays through this complicated mechanism scales with the development of the disk or is initiated above some threshold. However, we can speculate that the X-rays of γ Cas were not present circa 1937 when the disk was very weak or nonexistent. At the time the X-rays were first discovered in late 1975 (Jernigan 1976; Mason, White, & Sanford 1976), the current disk phase of γ Cas was already well underway and similar to its present state of development (Horaguchi et al. 1994). Ultimately, and on an unknown timescale, the current disk *will* dissipate, and so from our picture one anticipates that the X-ray emission will fade as well. Because the engine we outline is

complicated and because some X-ray properties of γ Cas itself are unpredictably (so far) time-dependent, it is unlikely that a γ Cas analog would show identical characteristics to γ Cas itself during the times we have observed it. For example, we would be mildly surprised if an analog should exhibit a 70 day modulation, and its X-ray light curve may or may not exhibit a clear rotational modulation at any given time. However, the production of hard X-rays and shots is expected to be a distinguishing characteristic. In this context, we suggest that the X-ray–variable source HD 110432 (B0.5 IIIe) might be a suitable candidate for observation. Reporting on *BeppoSAX* MECS observations, Torrejon & Orr (2001) have found that this source shows variable X-rays on timescales of 4 hr and (perhaps) a few minutes or less, an $L_{\rm X} = 7 \times 10^{32}$ ergs s^{-1} (2–10 keV), and, importantly, a hard X-ray spectrum consistent with a temperature of 10.55 keV. From its strong He I λ4471 emission and energy distribution in the UV and optical, it is also clear that the star has a strongly developed disk compared to most other Be stars (Zorec, Ballereau, & Chauville 2000; Moujtahid & Zorec 2000). Moreover, it appears in the same region of the H-R diagram as γ Cas, is a rapid rotator (Codina et al. 1984), and may exhibit variability on a rotation timescale in the optical region (Barrera, Mennickent, & Vogt 1991). In these ways the two stars appear to be nearly twins. A confirmation of even one more star that shows X-ray characteristics similar to the so far unique case of γ Cas would be critical to establishing the range of stellar and disk characteristics responsible for this rare X-ray phenomenology and to testing the plausibility of competing models.

REFERENCES

Airapetian, V. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 334
Balbus, S., & Hawley, J. F. 1991, ApJ, 376, 214
———. 1998, Rev. Mod. Phys., 70, 1
Barrera, L. H., Mennickent, R. E., & Vogt, N. 1991, Ap&SS, 185, 79
Berio, P., et al. 1999, A&A, 345, 203
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Brandenburg, A., Nordlund, A., Stein, R. F., & Torkelsson, U. 1995, ApJ, 446, 741
———. 1996, ApJ, 458, L45
Codina, S. J., de Freitas Pacheco, J. A., Lopes, D. F., & Gilra, D. 1984, A&AS, 57, 239
Cranmer, S. R., Smith, M. A. & Robinson, R. D. 2000, ApJ, 537, 433
Doazan, V., Franco, M., Rusconi, L., Sedmak, G., & Stalio, R. 1983, A&A, 128, 171
Harmanec, H. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 13
Harmanec, P., et al. 2000, A&A, 364, L85
Hawley, J. F., Gammie, C. F., & Balbus, S. A. 1996, ApJ, 464, 690
Henry, G. W. 1995a, in ASP Conf. Ser. 79, Robotic Telescopes: Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy, ed. G. W. Henry & J. A. Eaton (San Francisco: ASP), 37
———. 1995b, in ASP Conf. Ser. 79, Robotic Telescopes: Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy, ed. G. W. Henry & J. A. Eaton (San Francisco: ASP), 44
Hirata, R. 1984, in Proceedings of the Japan-France Seminar on Active Phenomena in the Outer Atmospheres of the Sun and Stars, ed. J.-C. Pecker & Y. Uchida (Paris: l'Observatoire de Paris), 115
Horaguchi, T., et al. 1994, PASJ, 46, 9
Jernigan, J. 1976, IAU Circ. 2900
Kubo, S., Murakami, T., Ishida, M., & Corbet, R. H. D. 1998, PASJ, 50, 417
Lamers, H. J., & Waters, L. B. 1987, A&A, 182, 80
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2000, A&AS, 147, 25
Mason, K. O., White, N. E., & Sanford, P. W. 1976, Nature, 260, 690
Millar, C. E., Sigut, T. A. A., & Marlborough, J. M. 2000, MNRAS, 312, 465
Moujtahid, A. et al. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 514
Moujtahid, A., & Zorec, J. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 55
Murakami, T., Koyama, K., Inoue, H., & Argawal, P. C. 1986, ApJ, 310, L31
Okazaki, A. T. 2001, PASJ, 53, 119
Pavlovski, K., Harmanec, P., & Bozic, H. 1997, A&AS, 125, 75
Poeckert, R., & Marlborough, J. M. 1978, ApJS, 38, 229
Quirrenbach, et al. 1997, ApJ, 479, 477
Robinson, R. D., & Smith, M. A. 2000, ApJ, 540, 474 (RS00)
Slettebak, A. 1982, ApJS, 50, 55
Smith, M. A. 1995, ApJ, 442, 812
Smith, M. A., & Robinson, R. D. 1999, ApJ, 517, 866
Smith, M. A., Robinson, R. D., & Corbet, H. D. 1998, ApJ, 503, 877 (SRC98)
Stee, Ph., & Bittar, J. 2001, A&A, 367, 532
Telting, J. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 422
Telting, J., & Kaper, L. 1994, A&A, 284, 515
Torkelsson, U., & Brandenburg, A. 1994, A&A, 292, 341
Torrejon, J. M., & Orr, A. 2001, A&A, 377, 148
Ulmschneider, P., Priest, E. R., & Rosner, R. 1991, Mechanisms of Chromospheric and Coronal Heating (Berlin: Springer)
Waters, L. B., et al. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 145
Waters, L. B. F., de Martino, D., Habets, G. M. H. J., & Taylor, A. R. 1989, A&A, 223, 207
Waters, L. B. F., Marlborough, J. M., van der Veen, W. E. C., & Taylor, A. R. 1991, A&A, 244, 120
White, N. E., Swank, J. H., Holt, S. S., & Parmar, A. N. 1982, ApJ, 263, 277
Zorec, J., Ballereau, D., & Chauville, J. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 502