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H ALPHA EMISSION IN CYGNUS X-1

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ABSTRACT

Observations are presented of the Hα region of the spectrum of Cygnus X-1, from spectrograms and Image Isocon scans. The feature is a broad emission broken by one or more blended absorption features. It is argued that the emission arises in an accretion ring surrounding the X-ray source. The configuration of the ring and evidence for mass-loss from its outer layer are discussed and some model calculations presented. An inclination of the system of $i \sim 30°$ is suggested, and a mass-ratio M_p/M_X of less than 2.

Subject headings: binaries — emission line stars — X-ray sources

I. INTRODUCTION

It has been shown (Hutchings *et al.* 1973; Smith, Margon, and Conti 1973) that the He II λ4686 emission in the spectrum of Cyg X-1 (=HDE 226868) has radial-velocity variations which are not in phase with those of the optical primary. It was suggested that this emission arises in a gas stream somewhere between the two objects in the system. In the hope of learning more about the regions giving rise to line emission, observations were made in 1973 of the Hα line in Cyg X-1, both photographically and with the Image Isocon camera. This paper presents the observations, the measurements made on them, and suggests interpretations in terms of a mass-exchange model.

II. OBSERVATIONS

The photographic observations were made (by A. P. C.) on the coudé spectrograph of the Kitt Peak National Observatory 84-inch (2.1-m) telescope and on the Cassegrain spectrograph of the Dominion Astrophysical Observatory 72-inch (1.8-m) telescope. They are listed in table 1. All phases are "photometric," from the ephemeris JD 2,441,561.222+5.60008 P, based on a recent spectroscopic period by Bolton (private communication). The Isocon observations were made (by J. W. G., G. A. H. W.) at a dispersion of 5 Å mm⁻¹ at the coudé spectrograph of the Dominion Astrophysical Observatory 48-inch (1.2-m) telescope. The apparatus and data are described fully elsewhere (Walker *et al.* 1971). The Isocon data, with 1 Å resolution, covered a useful range of some 250 Å and were obtained on five of six consecutive nights (i.e., through one orbital cycle). Additional stars used for spectrum and wavelength standards were HD 204172, 19 Cep, and α Cyg. Table 2 lists all these observations. Signal-to-noise figures may be compared with about 15 for the photographic observations: the resolutions are comparable.

The photographic spectra were measured for radial velocity on the KPNO Grant machine and the DAO ARCTURUS machine (see table 1). Density tracings were made to check on the general profile shape. The

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TABLE 1
SPECTROGRAPHIC DATA

DATE (1973–1974)	JD (2,440,000+)	DISPERSION EMULSION	PHASE (photometric)	Hα EMISSION VELOCITIES (km s⁻¹) Peaks	Center
June 10	1843.929	24 Å mm⁻¹ IIaF	0.48	−270, 168	−64:
June 11	1844.914	24 Å mm⁻¹ IIaF	0.66	98	...
June 14	1847.841	24 Å mm⁻¹ IIaF	0.18	−108	...
Nov. 21	2007.620	24 Å mm⁻¹ 098	0.71	130	...
Nov. 22	2008.627	24 Å mm⁻¹ 098	0.89	−233, 178	−37:
Nov. 23	2009.637	24 Å mm⁻¹ 098	0.07	−130	...
Jan. 3	2050.604	60 Å mm⁻¹ 098	0.39	−194, 310	164:
Jan. 7	2054.626	60 Å mm⁻¹ 098	0.11	−135, 325	77:

TABLE 2

ISOCON OBSERVATIONS

Date (1973 August)	Star	JD (2,440,000+)	Phase	S/N
19...........	Cyg X-1	1913.871	0.97	50
	HD 204172			64
	α Cyg			150
20...........	Cyg X-1	1914.849	0.15	47
	HD 204172			52
	19 Cep			87
	α Cyg			179
21...........	Cyg X-1	1915.808	0.32	47
	HD 204172			60
	19 Cep			125
	α Cyg			130
23...........	Cyg X-1	1917.787	0.67	32
	19 Cep			30
	α Cyg			184
24...........	Cyg X-1	1918.800	0.85	23
	HD 204172			88
	19 Cep			122

tracings are shown in figure 1, and it is clear that it is difficult to make consistent measurements on features of the profile. This is discussed further below.

Considerably more effort was required on the Isocon data. Ratios of raw scans of stars and dark readings taken each night revealed that on the last two nights changes occurred in the photocathode response. The data were split up; and the August 23 spectra, rectified in three sections, produced very similar results. This was not so for the August 24 data; and the second half of this night's results, on which continuum distortions were present and no Hα emission visible, was rejected.

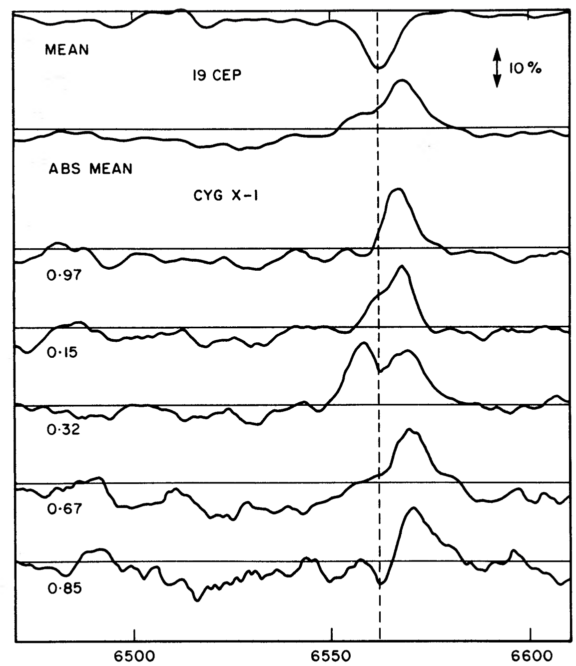

FIG. 2.—Isocon rectified tracings. *Top*, 19 Cep mean spectrum. *Middle*, Cyg X-1 mean spectrum in frame of primary star. *Lower*, individual night spectra.

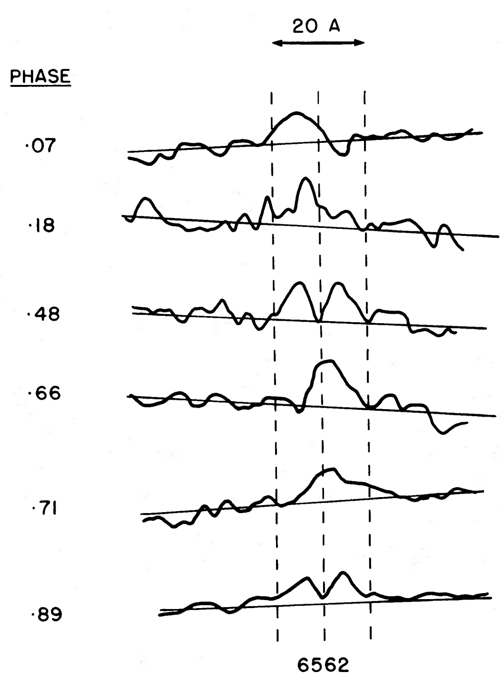

FIG. 1.—Density tracings, smoothed over 64 μ, of Hα photographic profiles.

Wavelength scales were established by position measurements on spectral features in the spectra of standard stars. On each night these scales were linear and agreed internally to within two data points. Uncertainties in wavelength from the mean dispersion curve for each night are of the order of 1 Å, or 50 km s^{-1}. The small number of lines and their weakness in the region of Hα makes the velocity scale less certain than that of the λ4686 observations of Hutchings *et al.* (1973). For this reason, the photographic velocities were a valuable check on the Isocon reductions.

All Isocon spectra were rectified to subjectively drawn continua, using the criteria (1) the continuum shapes should be similar to the appropriate standards and dark scans, and (2) spectra of the same star must be similar to within the noise level except for features which are definitely variable. The procedure was done completely independently by two of the authors (J. B. H., G. F.), and the agreement was found to be excellent. Figure 2 shows the rectified spectra of Cyg X-1 and a standard star.

III. THE PHOTOGRAPHIC DATA

While the photographic data are more noisy than the Isocon data, they cover a longer time span and indicate that the emission is intrinsically very variable. All the profiles (see fig. 1) may be inscribed in a broad single emission of approximately 20 Å width (and 30% peak intensity). The observed shapes broadly resemble those

TABLE 3

VELOCITY VARIATION FROM Hα REDWARD EMISSION EDGE

Phase	A 5%	B 10%	C 5%	D 10%	E 5%	F 10%	Mean
0.97	−104	−86	−105	−84	−102	−79	−93 ± 5
0.15	−116	−77	−105	−80	−89	−58	−88 ± 8
0.32	62	35	50	26	54	35	44 ± 6
0.67	47	46	42	60	35	49	47 ± 3
0.85	105	74	97	70	116	74	89 ± 8

NOTE.—Values in km s^{-1} from arbitrary (mean) V_0. A and B, observed profiles. C and D, HD 204172–Cyg X-1 profiles. E and F, 19 Cep–Cyg X-1 profiles.

of the Isocon data, with the following exceptions: (1) At phases 0.07 and 0.18 the shortward peak is much stronger than the longward. (However, at phases 0.11 and 0.39, of which tracings are not shown, the peaks are about equal.) (2) At phase 0.89 the shortward peak is seen. It is not clear from these data whether the emission as a whole undergoes radial-velocity changes, as the line wings vanish into the plate noise. However, the 0.18 and 0.71 profiles suggest an antiphase motion to that of the primary star. The observed profiles, however, cannot be produced only by a blend of stationary emission and an absorption component moving with the orbital motion of the primary; nor can they be produced by emission associated with the primary. Either the two features move in rough antiphase, or additional absorptions—predominantly negative in velocity—are present at times.

IV. THE ISOCON DATA

In the Isocon profiles only the redward peak is seen at all phases except 0.33. At most times, therefore, only a redshifted peak is seen, and the simplest explanation for this is that a blueshifted absorption is responsible. During the orbital cycle covered by the Isocon observations, there is no indication of activity on the redward peak, and it is possible that the velocity *variation* of the emission may be estimated by measurements of the redward edge of the profile. These are listed as columns A and B of table 3.

If we assume that the emission arises in a region separate from the primary star, we may subtract a standard spectrum from that of Cyg X-1 (after aligning absorption-line velocities) to obtain the true emission profile. The absence of appreciable emission in the standards used suggests that the Cyg X-1 primary ($M_v \simeq -6.3$ from Margon, Bowyer, and Stone 1973 and Bregman *et al.* 1973), if normal, should not contribute the observed Hα emission on its own (Rosendhal 1973). Very similar profiles result from the subtraction of either HD 204172 or 19 Cep spectra, and they are shown in figure 3. It is seen that the double feature at phase 0.32 is largely filled in, and that the variations between observations are in the shortward wing of a broad emission feature. An additional central absorption is suggested at phase 0.85. Measurements of the redward edge of these profiles yield the numbers in columns C, D, E, and F of table 3. These numbers are all shifted by the same (arbitrary) zero point, and the mean values are plotted in figure 4.

These velocities, which cover a single orbit, thus suggest that any emission velocity variation is not in phase with that of the primary absorption spectrum. Both sets of data, therefore, are consistent in this indication. Given that other absorption components do exist, which may confuse the picture, the velocities in figure 4 could arise from a region with an overall antiphase velocity variation, consistent with the mass ratio $M_p/M_X \sim 1.6$ derived by Hutchings *et al.* (1973), if this region is associated with the secondary.

An indication of the additional absorption present at phases other than 0.32 is obtained by subtracting the other profiles in figure 3 from this one. This was done (*a*) in the rest frame of the system and (*b*) in the supposed rest frame of the X-ray source. There are uncertainties as to which of these two is valid and also as to whether the phase 0.32 profile itself is anomalous. However, in all cases, the difference between the 0.32 profile and the others is (1) an absorption with velocity ~ -300 km s^{-1}, strongest at phase 0.15 and

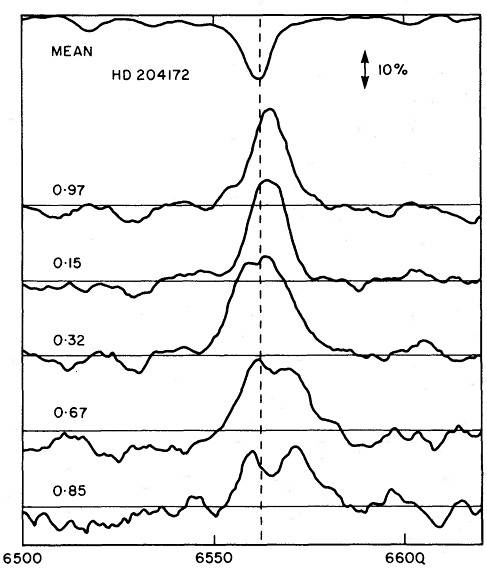

FIG. 3.—*Top*, HD 204172 mean Isocon spectrum. *Lower*, mean standard–Cyg X-1 profiles for individual nights.

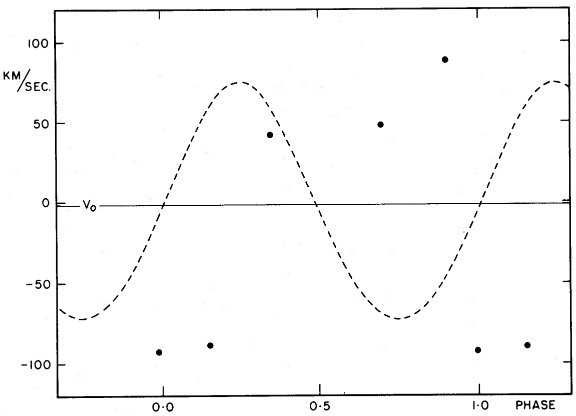

FIG. 4.—Mean Isocon velocities of Hα emission (*points*) and 1973 orbital velocity curve for primary (*line*).

weakest at 0.67, and (2) a further absorption at $\sim +50$ km s^{-1} at phases 0.67 and 0.85, stronger in the latter. Table 4 gives some numerical data from the Isocon profiles.

V. OTHER OBSERVATIONS

Spectrographic observations of Hα have been reported by Brucato and Zappala (1974). These show that (1) the double-peaked emission is seen between about phases 0.15 and 0.55 (photometric) and (2) the velocities of the *peaks* move *in phase* with the absorption velocities, but shifted by $\sim \pm 200$ km s^{-1}. These authors conclude that the emission is associated with the primary. We wish to show that this conclusion is not necessary, by two arguments.

1. If a profile is synthesized by a stationary emission (i.e., having no orbital motion) of 30 percent peak intensity and 20 Å width, and an absorption spectrum as given by the Isocon standard-star observations, having the orbital velocity of the Cyg X-1 primary, then the positions of the resultant two peaks show velocity variations exactly like those measured by Brucato and Zappala, and those given in our table 1. The synthesized profiles have a velocity amplitude which is ~ 60 percent of the absorption (although this varies with the exact profiles used). A best-fit sine curve through Brucato and Zappala's points has an amplitude of 80 percent of the absorption. Their observations are therefore consistent with a stationary emission line. Synthesis of profiles with an emission moving in antiphase with the absorption, as suggested above, yields apparent peak velocities which move slightly in antiphase with the absorption. However, the scatter of the reported velocities (mean error per point in the best fit is 41 km s^{-1}) and the other evidence presented here—particularly the disappearance of the shortward peak at most phases—indicates that additional effects are present.

2. The large width of the observed emission implies velocities of the order of 500 km s^{-1} or more. Such velocities are rarely seen in Hα in B supergiants and considerably exceed the escape velocity from the star. The only known exceptions are HD 2905 and HD 30614 (Rosendhal 1973), both of which are very different at Hα from HDE 226868. Association of the emission with the compact X-ray source, as proposed here, provides the only reasonable explanation of these velocities, considering the absence of observed features with high blueshifts or other indications of high mass loss (Hutchings 1970) in the absorption spectrum of the primary.

Finally, the Hβ line was examined for evidence of emission behavior. The data here are heterogeneous and, in some cases, marginal. Bolton (1972, 1973) has reported Hβ emission on the redward side of the absorption at phases near 0.75, but not blueshifted at phases near 0.25. If the extra absorption discussed above is usually present, this would account for Bolton's findings. Tracings from DAO spectra (30 Å mm^{-1} on IIIaJ emulsion) from 1972 also indicate the presence of Hβ redward emission roughly at phase 0.75, seen as an asymmetry in the line, and revealed by subtraction of spectra of HD 204172. Isocon scans at Hβ of Cyg X-1 and HD 204172 were also made in 1972, at phase 0.23. In this case, subtraction indicated a weak blueshifted emission. Finally, residuals of the Hβ absorption line velocity measured from DAO spectra, from the orbital velocity, reveal systematic differences in which Hβ is more negative through phases 0.4–0.8, and marginally more positive at phases 0.1–0.2. Bolton (private communication) reports similar effects. (We also note here that our measurements of He I λ6678 show this effect, although Brucato and Zappala's do not.)

We thus conclude that the behavior of emission at Hα is reproduced weakly at Hβ—i.e., emission which is not in phase with absorption, usually stronger on

TABLE 4

Hα PROFILE CHARACTERISTICS, ISOCON DATA

Phase	Observed EW (Å)	Absorption Subtracted EW (Å)	Absorption Subtracted Peak	Absorption Subtracted ½W (Å)	Additional Absorption EW (Å)	Additional Absorption Velocity (km s^{-1})
0.97	1.3	3.1	1.26	12	1.0	−230
0.15	1.5	3.3	1.27	13	1.3	−270
0.32	1.2 + 1.3	4.8	1.26	19	...	...
0.67	1.3	3.3	1.19	18	0.6, 0.6	−250, +60
0.85	1.3	2.8	1.16	19	0.7, 1.0	−250, +50

NOTE.—½W = full width at half maximum; peak = peak intensity/continuum.

its long wavelength side, and usually present to some extent. It is difficult to estimate the Balmer decrement, but it is certainly higher than that found in normal (i.e., radiation-dominated) emission stars, such as Be stars. We estimate the decrement to be about 10, which corresponds to the collision-dominated case 2*b* of Itoh and Kogure (1967).

VI. INTERPRETATION

The main results from the observations are (1) very wide emission (≥ 20 Å); (2) emission velocity variation out of phase with absorption, probably of slightly higher amplitude; (3) emission strongest through phases 0.15 to 0.55, and weakest at ~ 0.9; (4) additional absorption seen at most phases, with high negative velocity. We describe below a rough model which appears to be compatible with these phenomena.

The model is sketched in figure 5. The emission is supposed to originate in an accretion ring surrounding the X-ray source. It is confined to within some $\pm 35°$ of the equatorial plane: fed from without by a gas stream from the primary, its inner regions collapse on to a compact object to emit X-rays, while its outer regions (in the cone of sight at least) may expand at some 300 km s^{-1}. The observed lack, or minimum, of this absorption at roughly phase 0.3 may be associated with a bulge of higher density which is supposed to accumulate in gas streams of this nature (see, e.g., Prendergast and Taam 1974; Batten 1974). The extra absorption seen near phase 0.8 may be produced in the positive-velocity gas stream projected against the disk. The stream proposed from the λ4686 observations lies along this line, and the λ4686 emission may arise in the region of interaction of the stream and disk. The large width of the emission indicates rotational velocities of the order of 1500 km s^{-1} at $i \sim 30°$ or 1000 km s^{-1} at $i \sim 60°$, which are possible only around collapsars or white dwarfs.

Calculations were made of profiles from possible models of this nature by the method of Hutchings (1972*a*). It was found that at densities of $\sim 10^{14}$ particles per cm^3 a disk of radius 5×10^5 km will give rise to emission of the observed intensity by radiative de-excitation normal for a dilute radiation field. This is a rather uncertain point, as the mechanism exciting the radiation is not clear; but if these numbers are correct to within an order of magnitude, they indicate a central mass of some 10 $M_\odot$. If the disk were much smaller, the central mass would be lower (1 $M_\odot$) and densities high enough to cause opacity at all wavelengths. If the disk were 10 times larger, densities would be much lower, an appreciable contribution to the emission might then be expected from the stream, and the central mass would be far larger (100 $M_\odot$).

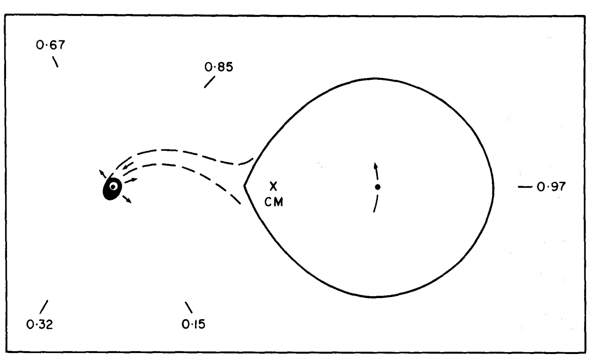

FIG. 5.—Sketch of model of Cyg X-1 in orbital plane. Lines of sight indicated for phases of Isocon observations.

Profiles, similar to the profiles illustrated in Hutchings (1972*b*), were calculated at two orbital inclinations. (1) $i = 30°$. The single-peaked structure is formed for a disk confined to within 35° of the orbital plane, provided that the rotational velocity falls by at least half its value through a distance increase of three times. Otherwise a double peak is formed. For a spherical envelope, a single peak is always formed. (2) $i = 60°$. The same results apply with the exception that the rotational velocity must be lower and fall at least 1.5 times faster for the disk model.

It therefore appears that angular momentum is not constant with radial distance in such a disk. This implies the existence of a viscous-type force which accelerates matter fed into the disk from outside.

The inferred absorptions are reproducible by models whose outer layers are expanding analogously to mass-loss supergiants (Hutchings 1970), with a terminal velocity of some 300 km s^{-1}.

The model described is similar to that described by Shakura and Sunyaev (1973) for an accretion ring. If the density of the disk is high enough in the equatorial plane the X-rays may be attenuated by it, providing energy for the outflow, and be visible to us only on account of the high inclination of the system. We also point out the absence of X-radiation from equator-on-black-hole candidates (e.g., β Lyr, HD 187399, HD 72754; see Hutchings 1974).

It is tempting to try to estimate the mass-exchange rate, but the data do not seem certain enough to give more than a very rough estimate. A single star of the luminosity and assumed mass of HDE 226868 shows little or no Hα emission, and mass-loss rates are probably 10^{-7} $M_\odot$ or less per year. The tidal action of the companion to HDE 226868 may increase this; but the absence of Balmer emission, associated with the primary or the gas stream, still leaves 10^{-7} $M_\odot$ per year as an upper limit. Presumably a large fraction of this would go toward the companion. If we ascribe the additional absorption at ~ 0.8 phase to line-of-sight effects along a gas stream and the other absorptions to mass loss from the disk, then it appears that only a small fraction of the transferred mass falls onto the compact object. However, the expansion appears not always to be present, and the estimates are biased by our presumed high inclination to the orbital plane. These figures at any rate seem compatible with the 10^{-9} $M_\odot$ per year proposed by Shakura and Sunyaev for the formation of a disk.

VII. OTHER EVIDENCE

Further photometry of the system in 1973 (R. W. Hilditch, E. N. Walker, private communications) indicates that the light variation may have changed slightly since 1972. These changes (~ 0.01 mag) are consistent with changes in the gas stream opacity as they occur at phases 0.5–0.75. More important is the finding of a possible short "eclipse" in the low-energy X-rays (K. O. Mason 1973, report at IAU, Sydney). This is very short and does not appear to have exactly the known orbital periodicity. The phenomenon thus implies either $i \sim 66°$ to give a grazing eclipse, or that the eclipse is by some quasi-stable region of high density in the stream or disk.

As shown by several workers (e.g., Bolton 1972), the inclination required by a normal primary star near its Roche limit, with $q \leq 2$, is $\leq 30°$. If $i \sim 66°$, the inferred primary mass-radius relation is normal for $q \sim 4$, $M_p \sim 28\, M_\odot$, $M_X \sim 7\, M_\odot$, and $R \sim 0.9\, R_{\text{Roche}}$. If q is kept at the preferred value of 1.6 for $i \sim 66°$, then $M_p < 10\, M_\odot$ and the primary would be a peculiar object—possibly the helium-burning core of a once massive star. Until such objects are positively identified, it is impossible to know what their optical appearance would be. Should the inclination be large, the inferred rotation characteristics of the disk would be as noted above.

We conclude that the evidence from the Hα emission in Cyg X-1 is consistent with the model of Hutchings *et al.* (1973), supporting the mass-ratio and gas-stream configuration. High-quality Hα observations appear to be highly desirable.

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