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New forbidden and fluorescent Fe III lines identified in HST spectra of η Carinae*

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Abstract. We discuss the origin of eight emission lines in the spectra of gas blobs close to the central star of η Carinae. The spectra have been obtained with the Goddard High Resolution Spectrograph (GHRS) and the Space Telescope Imaging Spectrograph (STIS) onboard the *Hubble Space Telescope*. Between 2400 and 2500 Å five narrow lines are identified as new forbidden lines of doubly ionized iron, [Fe III]. We present gA-value data for the corresponding transitions, which combine two different metastable configurations of Fe III. An anomalous intensity of the narrow Fe III line (UV 34) at 1914 Å is explained as fluorescence due to HLyα pumping. A level mixing of about 1% increases the f-value of the pumped excitation channel by more than two orders of magnitude, which makes the pumping efficient and the fluorescence significant. We introduce a new designation for fluorescence lines photoexcited by an accidental resonance, eg. ⟨Fe III⟩ in the case of doubly ionized iron.

Key words: atomic processes – line: identification – stars: individual: η Car – stars: variables: general – ultraviolet: stars

1. Introduction

The luminous blue variable star η Carinae has been extensively studied with the Hubble Space Telescope (HST), using both the Goddard High Resolution Spectrograph (GHRS) (Davidson et al. 1997) and the Space Telescope Imaging Spectrograph (STIS) (Davidson et al. 1999, Gull et al. 1999).

The high spatial resolution of HST permits the inner core region around the central star to be studied in detail, and spectra of various condensations close to the star have been recorded (Davidson et al. 1995). Of special interest are the so called Weigelt blobs (Weigelt & Ebersberger 1986, Davidson et al. 1997), which are located in an equatorial disk only a few tenths of an arcsecond from the central star. The plane of the disk includes the central star and is perpendicular to the propagation direction of the bipolar lobes, formed in the Great Eruption 150 years ago. (For most recent studies of η Carinae, see proceedings from an international meeting about that particular star in 1998 (Morse et al. 1999.))

Spectra of the Weigelt blobs show little resemblance to the stellar spectrum itself (see e.g. Fig. 1 in Davidson et al. 1995). A detailed line list with identifications of the blob spectrum in the region 1640-10400 Å has been prepared by T. Zethson and it is ready for publication. The spectrum contains numerous narrow emission lines of Fe II that are either collisionally excited forbidden transitions, [Fe II], or radiatively excited fluorescence lines, ⟨Fe II⟩. We will use this latter notation throughout the paper for fluorescence lines that result from photoexcitation by accidental resonances. A set of such fluorescence lines originates from the decay of a particular energy level, which has been selectively excited by photons from a strong line, the pumping line (e.g. HLyα). The pumping line should agree in wavelength with the pumped transition, the excitation channel, and thus populate the upper level of the fluorescence line(s).

In this paper we report newly identified forbidden transitions of doubly ionized iron, [Fe III], and a previously unexplained fluorescence line of the same ion, ⟨Fe III⟩, photoexcited by HLyα. The new [Fe III] lines appear in the 2400–2500 Å region, and they have also been seen in spectra of other objects. The ⟨Fe III⟩ line belongs to the multiplet UV34 located around 1900 Å. The new identifications reported here were discussed briefly at the η Carinae meeting mentioned above (Johansson & Zethson 1999).

2. New forbidden [Fe III] lines

The ground configuration of Fe III, $3d^6$, has 14 experimentally established LS terms, of which a^5D is the ground term. Forbidden transitions between the energy levels of this even-parity configuration have been observed in spectra of various emission line objects, e.g. RR Tel, and the transition proba-

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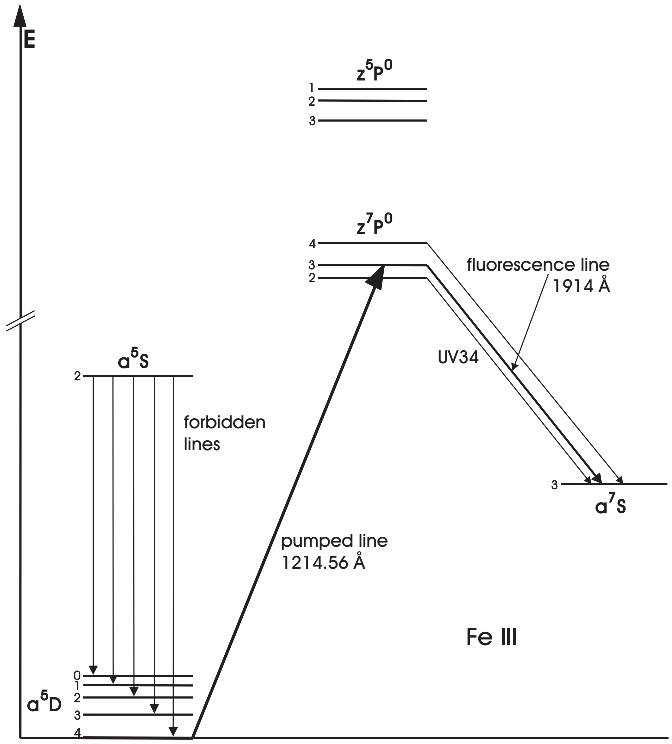

Fig. 1. Partial energy level diagram of Fe III, showing the energy levels involved in the forbidden lines and the fluorescent line discussed in the text. The energy axis is not to scale. Numbers beside the levels are J-values.

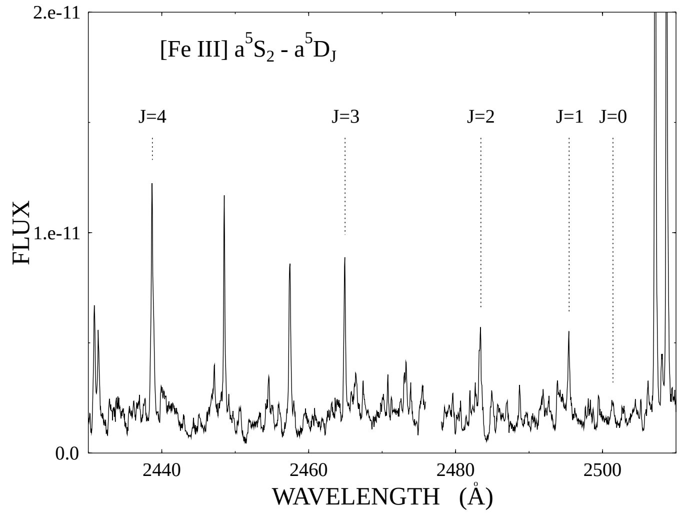

Fig. 2. GHRS spectrum from September 1996 of the blobs located close to the central star in η Carinae. The indicated lines are newly identified [Fe III] lines of the a^5S_2 - a^5D_J multiplet. The J-values of a^5D are given in the figure. The other narrow lines in the spectrum are fluorescent Fe II lines.

bilities have been calculated by Garstang (1957) and recently by Quinet (1996). However, Fe III has another low even-parity configuration, $3d^5 4s$, of which some of the lower levels are metastable and located well below the lowest level of opposite parity. A partial term diagram with the actual LS terms indicated is shown in Fig. 1. The a^5S term of $3d^5 4s$ combines with the ground term, a^5D, in electric quadrupole (E2) transitions giving five predicted forbidden lines. Some of them were suggested by Johansson (1984) as possible identifications in IUE spectra of RR Tel and KQ Puppis, but they needed calculated A-values in order to be confirmed. They have to our knowledge not been reported after that in the literature. However, similar forbidden [Fe III] lines between other 4 s terms and the ground term have been identified in the solar spectrum (Jordan et al. 1986). The forbidden lines reported in this paper have not been observed in any laboratory source, but the wavelengths can be derived from experimental energy levels (Ekberg, 1993). The lines are tabulated in Table 1 together with newly calculated transition probabilities using the Cowan code (Cowan 1981). The calculation of the E2 transition probabilities are based on Ekberg's (1993) values of the Slater parameters for the $3d^5 4s$ and $3d^6$ configurations and the electric quadrupole moment obtained from the Cowan code.

In GHRS and STIS spectra of the Weigelt blobs in η Carinae we have observed narrow emission lines whose wavelengths correspond to the wavelengths derived for the [Fe III] transitions from a^5S_2 to the fine structure levels of the ground term a^5D. An extract of the GHRS spectrum of η Carinae is shown in Fig. 2, where the newly identified [Fe III] lines are indicated. The wavelengths and relative fluxes of the stellar lines have been measured in the GHRS spectrum of the blobs, and they are included in Table 1. The lines are prominent in the spectra, and the measured fluxes match well the calculated transition probabilities. One component is blended with another Fe III line, which is the LS-forbidden intercombination line of UV multiplet 47 at 2438.179 Å**(**λ_{air}**)**. However, the other permitted Fe III line of UV47 is not observed in our η Car spectra, and we believe that all the intensity of the 2438 Å feature belongs to the forbidden transition.

The [Fe III] lines are blueshifted by about 41 km s^{-1}, which matches the radial velocity of the narrow fluorescent Fe II lines observed in spectra of the same spatial region of η Carinae (Zethson et al. 1999, Davidson et al. 1997). Recent STIS spectra of the same spatial region also contain numerous [Fe II] lines.

The three strongest of the newly identified [Fe III] lines have also been identified in the UV spectrum of RR Tel (Hartman & Johansson 2000). Two of them were included as unidentified features in the line list by Penston et al. (1983), whereas the 2438 Å line was identified as UV47 of Fe III, as discussed above.

3. New fluorescent ⟨Fe III⟩ lines

The permitted Fe III multiplet UV34 around 1900 Å (see Fig. 1) yields in general the strongest Fe III lines in the combined ultraviolet and optical spectral region of emission line objects. The resonance lines and other ground term transitions of Fe III appear below 1150 Å (Ekberg, 1993). The ultraviolet multiplet UV34 corresponds to the transition between the lowest LS terms of the two lowest excited configurations of Fe III, i.e. $3d^5(^6S)4s\ a^7S$ - $3d^5(^6S)4p\ z^7P$, which gives three lines, a^7S_3 - z^7P_4 at 1895.473 Å, a^7S_3 - z^7P_3 at 1914.066 Å and a^7S_3 - z^7P_2 at

Table 1. Data for the new forbidden a^5S_2 - a^5D_J transitions of [Fe III] observed in GHRS spectra (see Fig. 2) of the Weigelt blobs in the core region of η Carinae. (Note that the comparison is done for vacuum wavelengths, but we also give the air wavelengths in the table. Wavelengths are derived from energy levels (Ekberg 1993).)

a^5D_J	λ_{lab}(air,Å)	λ_{lab}(vac,Å)	λ_{star}(vac,Å)	$\Delta\lambda$ (Å)	I_{star}	gA (s^{-1})
4	2438.280	2439.019	2438.68	0.34	105	111
3	2464.477	2465.222	2464.90	0.32	75	80
2	2483.010	2483.760	2483.37	0.39	40	55
1	2495.013	2495.755	2495.41	0.34	35	32
0	2501.929	2501.683	2501.37	0.31	10	10

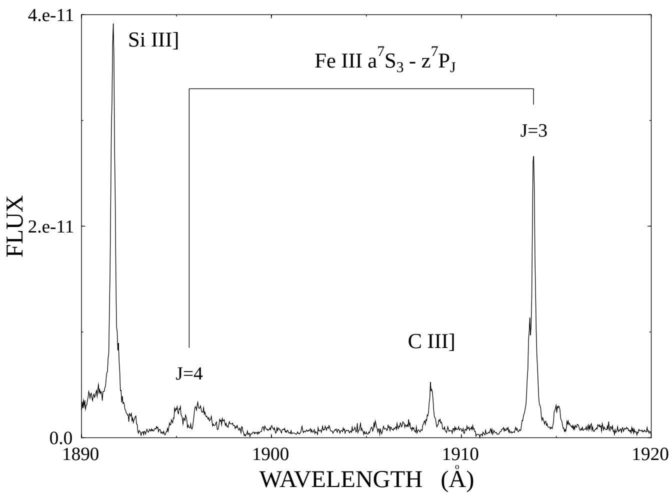

Fig. 3. GHRS spectrum from September 1996 of the blobs located close to the central star in η Carinae. The indicated lines are Fe III lines of UV34. The double-peaked J=4 feature is scattered light from the star, superimposed by Ni II absorption. The double-peaked J=3 feature is scattered light from the star, superimposed by Mn II absorption and a narrow fluorescent component formed in the blob. The fluorescent component is discussed in detail in the text.

1926.320 Å. The intensity ratios of the three lines, considering the small fine structure splitting of the z^7P term and assuming a thermal population, is given by the ratios of the statistical weights, 2J+1, of the upper levels, i.e. 9:7:5. This is confirmed by values of the weighted Einstein coefficients, gA, calculated by Ekberg (1993): $6.1 \cdot 10^9$ (s^{-1}), $4.6 \cdot 10^9$ and $3.2 \cdot 10^9$, respectively, giving the ratios 9:6.8:4.7. (The A-values calculated by Nahar & Pradhan (1996) are 25% smaller but give the same ratios.)

Fig. 3 shows GHRS spectra from September 1996 of the blobs in η Car with two of the three Fe III UV34 lines - the a^7S_3 - z^7P_4 transition at 1895.473 Å and a^7S_3 - z^7P_3 at 1914.066 Å - falling in the observed region. The 1914 Å line is more than 10 times stronger than the 1895 Å line in the observed spectrum, which implies a selective excitation of the z^7P_3 level. Our STIS spectra cover also the 1926 Å line, which is about half the intensity of the 1895 Å line, as predicted by theory. The z^7P_2 level is thus not overpopulated. These estimates of the observed intensity ratios are based on the assumption that the left component of the features at 1895 Å and 1914 Å in Fig. 3 is the Fe III line. However, the two lines at 1895 Å and 1914 Å have an unidentified redshifted companion, which could imply that the Fe III lines have the broad profile seen for lines resulting from scattered light from the star. In the case of Fe III this broad emission contains central absorption, which is not observed for other lines. This scenario gives some strange consequences: the broad Fe III features in the blob with their central absorption seem to be redshifted, and the narrow component is on the blue side of the presumably broad Fe III line at 1914 Å whereas the narrow Si III] component at 1890 Å is on the red side. However, the difference in wavelength shift between these narrow components is only 0.1 Å or 16 km s^{-1}.

To explain this anomaly we have in Fig. 4 plotted the spectrum of the star (solid curve) together with the blob spectrum (dotted curve), both obtained with STIS in February 1999. It is clear that the Fe III lines are present with P Cygni profiles in the spectrum of the star. The broad base features seen in the blob spectrum are thus scattered light from the star, but due to the P Cygni absorption of the Fe III lines the base of the scattered line is not that broad as it is for the Si III] line, which has no P Cygni absorption. The apparent redshift of the broad Fe III features in the blob spectrum is thus due to the their P Cygni profiles in the star's spectrum. The same is true for the apparent anomaly in the relative placement of the narrow components of the Fe III line (1914 Å) and the Si III] line (1890 Å), as the latter has no absorption in the blue wing in the star. Finally, the central absorption observed in the Fe III lines has not its origin in Fe III. It is due to two different lines that happen to coincide in wavelength: In the 1895 Å feature there is absorption from a ground state transition of Ni II (UV1) at 1896.15 Å and in the 1915 Å feature there is a low excitation Mn II line (UV10) at 1915.10 Å. The identified absorption features are verified by observation of other absorption lines of Mn II and Ni II. Thus, the central absorption is not due to Fe III, which is consistent with the absence of absorption in the third Fe III line at 1926 Å.

The conclusion of the discussion in the previous paragraph is that there is no narrow line contribution from the blobs to the Fe III features observed at 1895 and 1926 Å in the blob spectrum. They are both built up by scattered line radiation from the star. There is thus only an anomalous intensity in the narrow component of the 1914 Å feature, which is due to fluorescence. It has in the identifications of IUE spectra been described as a fluorescence feature pumped by HLyα without any details about the pumping channels (Viotti et al. 1998). It is also observed as a blue shifted emission feature in KQ Pup (Rossi et

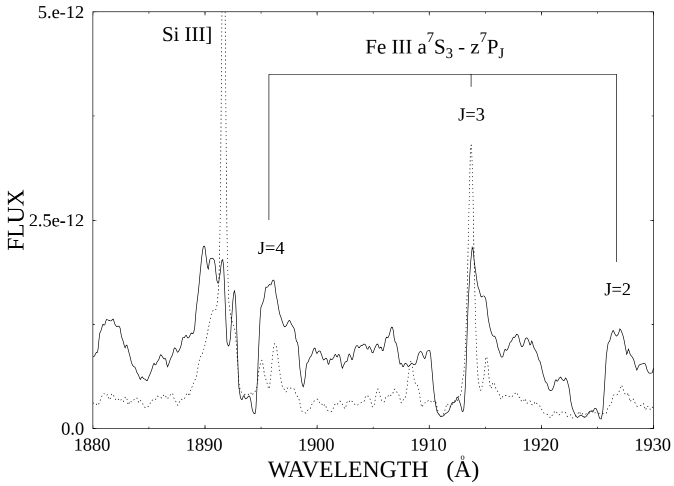

Fig. 4. STIS spectrum from February 1999 of the central star (solid curve) compared with the spectrum of the blobs (dotted curve) in η Carinae of about the same wavelength region as shown in Fig. 3. This spectrum also includes the J=2 feature. The figure shows the agreement between the P Cygni type Fe III emission in the star and the broad features in the blobs. It also shows the absence of absorption in the J=2 feature, verifiying the accidental coincidence with Ni II and Mn II of the J=4 and J=3 features.

Table 2. Data for those lines of the spinforbidden Fe III multiplet 3d^6 a^{5}D - 3d^{5}4p z^{7}P^o, whose wavelengths are within $\pm$ 10 Å from HLyα. One of them acts as an excitation channel in HLyα pumping of Fe III.

z^{7}P$_J$	a^{5}D$_J$	λ(Å)^a	log gf^b	log gf^c	I$^a_{lab}$
4	4	1207.049	-4.40	-4.35	-
4	3	1213.432	-5.11	-5.07	-
3	4	1214.562	-2.41	-2.66	10
3	3	1221.025	-3.10	-3.39	^{d}
3	2	1225.555	-4.02	-4.34	3
2	3	1226.000	-2.96	-3.22	9

[a] From Ekberg (1993). Wavelengths are derived from the energy levels.
[b] From the Kurucz (1988) database on
http://cfa-www.harvard.edu/amdata/ampdata/kurucz23/sekur.html
and included in Morton (1991)
[c] From Ekberg (1993) and new data.
[d] This line is blended by a Fe VI line in the laboratory spectrum.

al. 1998). The large overpopulation of the upper level of the 1914 Å line can be explained by a selective excitation provided by HLyα photons. In this process HLyα photons pump Fe^{2+} ions from the ground term a^{5}D to the upper levels of z^{7}P. (The a^{5}D - z^{7}P multiplet is not included in the UV multiplet table, and following Moore's extended numbering system for revised spectra it should be labeled UV 0.01. However, data for the multiplet are given in Morton's compilation of resonance absorption lines (Morton 1991)). The pumping occurs thus in the spin-forbidden transition 3d^6 a^{5}D - 3d^{5}4p z^{7}P (see Fig. 1). In general, we should expect low transition probabilities for these LS-forbidden excitation channels. In Table 2 we give the rest wavelengths for those Fe III lines of UV 0.01, which are within $\pm$ 10 Å from HLyα at 1215.667 Å and therefore could be potential excitation channels. The wavelengths are derived from the energy levels in Ekberg (1993), which also provides the laboratory intensities. We have also inserted log gf-values from Ekberg (1993) and from new calculations as well as from Kurucz's (1988) database as given by Morton (1991). As the gf-values are critical in the explanation of the fluorescence we quote two independent calculations. The non-linear laboratory intensities are fairly consistent with calculated log gf-values, except for the 1221 Å line, which is missing in Ekberg's line list (1993). An examination of the laboratory spark spectra shows that the Fe III line at 1221 Å is masked by a Fe VI line.

By only considering the wavelength differences between the Fe III lines in Table 2 and HLyα it is clear that the J=3 level has the greatest probability of being photoexcited via the 1214.56 Å transition, about 1.1 Å from the rest wavelength of HLyα. This is in agreement with the line enhancement in the observed spectrum. The line at 1213.43 Å in Table 2 is 2.2 Å away from HLyα and it should pump the J=4 level of z^{7}P. Since there is no indication of enhancement of the 1895 Å line, the J=4 level is not overpopulated. This could then put constraints on the FWHM of HLyα in the pumping medium of the stellar environment. However, the oscillator strength of the 1213.43 Å line is more than two orders of magnitude smaller than the gf-value for the 1214.56 Å line. If we suppose that HLyα could pump the J=4 level in the 1213.43 Å channel it would yield a population that is about 500 times smaller compared to the J=3 level. Hence, the absence of fluorescence in the 1895 Å is consistent with the observed intensity of the 1914 Å line and the calculated f-values in Table 2. No conclusions can be drawn about the width of HLyα. The absence of fluorescence in the 1926 Å line is, however, more probably the result of the large distance ($>$10 Å) between the closest excitation channel (1226.01 Å) and HLyα.

In general, the f-values (or A-values) of the strongest line from each level has about the same magnitude within a given multiplet, but that is not true for the a^{5}D - z^{7}P mutiplet, as judged from calculations and laboratory intensities in Table 2. The explanation to the large differences in oscillator strengths between transitions to J=4 compared with transitions to J=3 or J=2 of z^7P can only be explained by level mixing. A low transition probability is what should be expected for the intercombination transitions from z^{7}P but it is only small for the J=4 level ($\lambda\lambda$1207, 1213 in Table 2). The J=3 and J=2 levels of z^{7}P have about 1% ^{5}P character due to mixing with the quintet term, z^{5}P, located about 0.1 eV above z^{7}P (see Fig. 1). Since the z^{5}P term has the J-values 1, 2 and 3 the z^{7}P levels with J=2 and J=3 can mix with z^{5}P, but not the J=4 level. This is verified by the calculation of Ekberg (1993), which gives a purity of 100% for the J=4 and more than 99% for the other two J-values. Thus, a contribution of less than 1% from the z^{5}P levels to the z^{7}P$_2$ and z^{7}P$_3$ levels is enough for increasing the oscillator strength by more than two orders of magnitude.

4. Conclusion

The many optical [Fe II] lines in the STIS spectrum of the gas blobs, located only a few tenths of an arcsecond from the central star of η Carinae, are accompanied by strong newly identified [Fe III] lines in the satellite UV region. The lines correspond to a transition between the two lowest configurations of Fe III, which have the same parity. Transitions within the ground configuration have earlier been treated theoretically, and the corresponding lines have been identified in optical spectra of various objects, e.g. η Carinae. The observed stellar intensities of the new forbidden lines between 2400 and 2500 Å agree well on a relative scale with newly calculated transition probabilities. As a complement to [Fe II] the new [Fe III] lines may be of value for density measurements and abundance determinations.

The presence of only one of the three components of Fe III multiplet UV34 as a narrow feature in the blob spectrum is explained as a case of fluorescence. The upper level of the 1914 Å line is selectively excited by HLyα, and due to a level mixing in Fe III the pumping is particularly efficient. The oscillator strength for the pumped transition, which is close in wavelength to HLyα, is enhanced by at least two orders of magnitude due to the level mixing. The upper level of the normally strongest line in UV34 at 1895 Å could in principle also be pumped in a transition only 2.2 Å away from HLyα. However, this pump channel is a factor of 500 fainter than for the 1914 Å line due to the absence of level mixing. Potential pump channels for the third UV34 line at 1926 Å is more than 10 Å from HLyα. Thus, level mixing and an accidental wavelength coincidence between Fe III and HLyα cause the enhancement of the 1914 Å line.

Based on the data in Table 2 one could expect that multiplet UV 34 of Fe III should in astrophysical emission line spectra show a) one component at 1914 Å if H Lyα pumping is the dominant excitation mechanism b) two components at 1914 Å and 1926 Å if continuum photons excite the upper levels c) three components if the upper levels are excited thermally or by recombination. The UV 34 multiplet of Fe III can thus be used for determining whether the excitation source is blackbody radiation from the central star with substantial flux around 1215 Å (case b) or monochromatic HLyα radiation pumping one channel (case a). In the present case, we observe one component of UV 34 in the blob of η Carinae, but it is not clear whether the HLyα pumping radiation comes from the central star or internally from the blob. It is not possible at this stage to draw any astrophysical conclusions from the fluorescence lines of Fe III, but after a systematic study of all fluorescence lines we will try to investigate more in detail the possible diagnostic value behind these lines.

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