MASS LOSS IN RED GIANTS

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On high-dispersion spectrograms of some luminous M giants, the zero-volt lines of all abundant atoms and ions are double. (Fig. 1 (a), Pl. I, p. 112). This spectroscopic peculiarity was discovered by W. S. Adams and Miss MacCormack (1935) [1], who wrote that "a possible explanation of the origin of the abnormal lines...... may be an envelope of gas surrounding the stars and expanding with a moderate velocity". Recently it was found that some of the abnormal lines which occur in the M 5 II star α Herculis can also be seen in the spectrum of its visual companion, a giant G-type star [2]. In this system, it is clear that the Adams-MacCormack model is correct: both stars are enveloped in gas that has been ejected from the M star (Fig. 2). Moreover, the

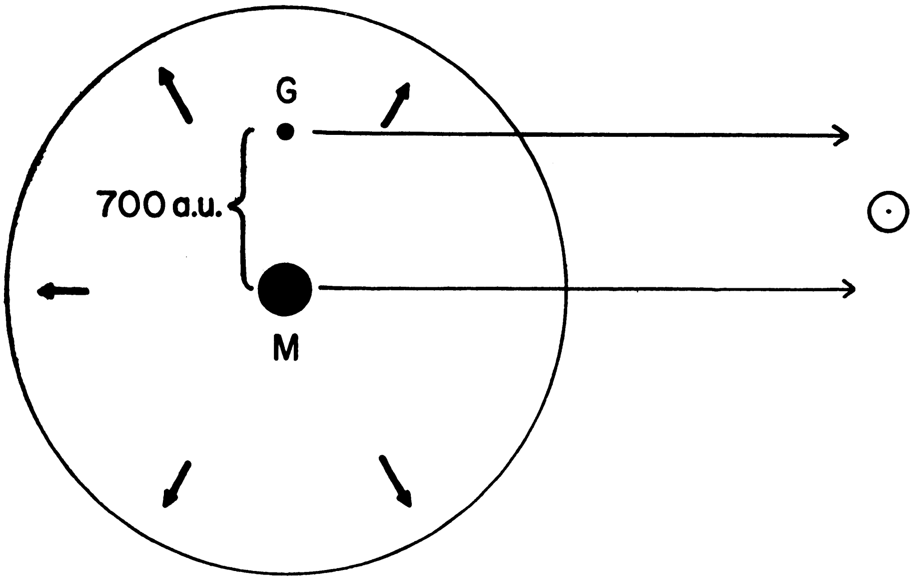

FIGURE 2. Model of the α Herculis system. The G-type visual companion lies within the expanding envelope of the M-type primary star.

circumstellar envelope of α Herculis must measure at least 2000 astronomical units in diameter, and in it the gas velocity exceeds the velocity of escape. The M star is clearly losing mass to the interstellar medium, at a rate that has been estimated to be about 10^{-7} solar masses per year.

The duplicity of α Herculis evidently plays no appreciable role in its ejection of matter; the G-type companion serves only as a very convenient probe for the detection of the remoter parts of the circumstellar envelope. There is reason to believe, therefore, that double resonance lines in late-type giants may indicate that many or all of these stars have circumstellar envelopes comparably large with that of α Herculis, and that all are losing mass at a comparable rate. If so, the red giant branch of the HR diagram may represent the chief site of the mass-loss that must attend the ultimate transformation of initially massive stars into white dwarfs [3].

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At the Mount Wilson and Palomar Observatories, an attempt is now being made to find in which red giants the doubling of resonance lines can be seen, and to establish the circumstellar origin of these lines wherever possible. Only a preliminary account of some results can be given at this time. The observations at hand make it clear that in different red giants the abnormal components of strong resonance lines occur with widely different strengths. The Ca II lines are always the strongest of the abnormal group, and their visibility is further enhanced because they are commonly superposed on emission lines. Adopting the terminology of the solar spectroscopists, we designate these emission lines as H_2 and K_2, and the absorption reversals within them as H_3 and K_3. The wide absorption lines produced in the reversing layer are then H_1 and K_1.

The lines K_3 and H_3 are strong enough for detection at a dispersion of 20 A/mm in the spectra of nearly all red giants. However, the abnormal components of other lines can generally be seen only at a dispersion of 10 A/mm or greater; some early M giants show none even at 2.3 A/mm. Unfortunately, the detection of K_3 and H_3 is insufficient evidence for concluding the existence of a circumstellar envelope. In many red giants, these lines must be attributed to the chromosphere. They generally indicate a small velocity of contraction towards the reversing layer [4]; in spectroscopic binaries, they show the same orbital motion as the reversing layer; and, when fully resolved, they reveal central intensities which are characteristically high. To demonstrate a true circumstellar envelope around a star, it is therefore generally necessary to

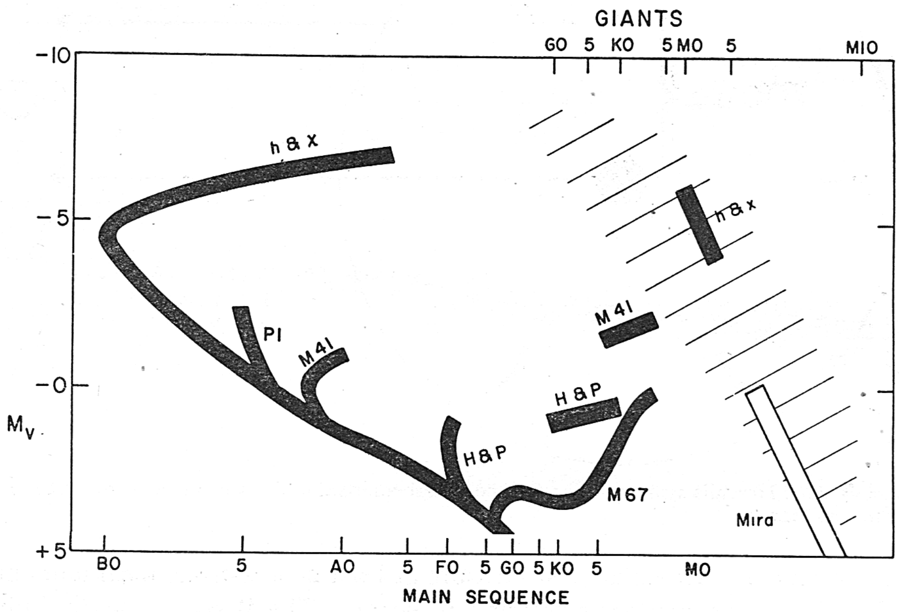

FIGURE 5. A composite HR diagram for galactic clusters, adapted from A. R. Sandage, *Ap. J.*, **125**, 435, 1957. Stars lying in the shaded area usually (always?) show spectroscopic evidence of mass-loss when observed at high dispersion; outside this area, stars do not show circumstellar features.

use a dispersion high enough to resolve the profile of K_3 and H_3, and/or to reveal the doubling of other strong resonance lines. When this is done, it is found that the Ca II reversals with deep, rectangular profiles correlate well in strength with comparable lines of other abundant atoms and ions (Fig. 3, Pl. II). The indication is that these lines do arise in circumstellar envelopes, and that these envelopes have closely comparable ionization in different stars.

The radial velocities from the different circumstellar (CS) lines generally agree in indicating an expansion of 5 or 10 km/sec relative to the reversing layer. However, H_3 and K_3 usually differ significantly from the other CS lines. In some cases, but not in all, this discordance can be attributed to the effect of unresolved interstellar components. If stratification effects are responsible, they could invalidate the ionization calculation for the envelope of α Herculis, and hence the mass-loss determination as well. More data will needed to clarify this important point.

In a few visual binaries involving M giants, K_3 and H_3 can be seen in projection against the spectrum of a companion of earlier type, as in the α Herculis system. Mira is an interesting case of this kind (Fig. 4 (a), Pl. III, p. 112). Another may be α Scorpii (Fig. 4 (b), Pl. IV, p. 112); although here it is more difficult to rule out the possibility that the observed features are really interstellar lines. In several spectroscopic binaries where the primaries are M giants with deep Ca II reversals, H_3 and K_3 do not show the orbital motion that is indicated by the reversing layer. Either they are stationary, or—if blended with strong chromospheric components—variable, in phase with the reversing layer but with diminished amplitude. A good example is the M 5 III star RR Ursae Minoris (Fig. 1 (b), Pl. I, p. 112), which is a single-line spectroscopic binary with a period of 750 days.

Among the red giants in which a true circumstellar (CS) spectrum appears to be present, the CS lines tend to strengthen as the spectral type grows later and/or as the absolute magnitude grows brighter. At 10 A/mm, the CS spectrum can generally be recognized as such in stars that populate the HR diagram above a line running from $M_v = -3$ at Mo to $M_v = 0$ at M5. A few M stars that lie well below this line (e.g., δ Oph, $M_v = -0.4$, Mo) have been observed at higher dispersions and show probably CS components at H and K. Similar features are also known in some K supergiants, and in a few long-period variables with types later than M5. A recent strong 10 A/mm spectrogram of the long-period-variable star χ Cygni at maximum brightness shows conspicuous doubling of all intense resonance lines. Circumstellar features probable occur also in the spectra of some N and S stars with effective temperatures and luminosities that are comparable with those of M giants and supergiants. Based on the material now at hand, we may conclude that most stars show some CS absorption lines when observed at 4.5 A/mm, provided they lie within the shaded domain of the HR diagram of Fig. 5.

Despite these correlations with type and luminosity, an appreciable dispersion exists in the CS line strength at any one point in the HR diagram. The differences among the supergiants α Ori (M2Ib), α Sco M1:Ib), μ Cep (M2Ia), and VV Cep (M2Iab) are a good example (Fig. 3).

In the last analysis, we may well have to abandon the sharp distinctions that have been drawn here between lines produced in the reversing layer, the chromosphere, and the CS envelope. There is some evidence from the radial velocities, and from central intensities of emission lines and absorption lines alike, that all lines are more or less affected by stratification effects in the enormously deep, differentially expanding atmospheres of the later red giants. Probably we shall have to conclude, in the end, that such atmospheres do not closely approximate a state of static equilibrium, but rather a steady state of outflow.

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[2] Deutsch, A. J., *Ap. J.*, **123**, 210, 1956.
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[4] Wilson, O. C., and Bappu, M. K. V., *Ap. J.*, **125**, 661, 1957.

Captions for the plates

FIGURE 1 (*a*). A portion of Pb 3457, a 4.5 A/mm spectrogram of α Orionis. Note the doubled resonance lines of Mn I and Sr II.

FIGURE 1 (*b*). Two 10 A/mm spectrograms of the M5 III spectroscopic binary RR Ursae Minoris, in the region of the K-line. Top, Pc 3309, 1957 Aug. 16; bottom Pc 3945, 1958 Aug. 26.

FIGURE 3. Enlargements from spectrograms of M stars Original dispersion, 4.5 A/mm.

FIGURE 4 (*a*). Enlargements from spectrograms of Mira; original dispersion, 10 A/mm. The top spectrogram shows the region of the K-line in the M5 II star α Herculis. The middle one shows Mira near maximum (phase -43^{d}), when the spectrum is dominated by the long-period variable. The bottom spectrogram shows Mira near minimum (phase $+194^{d}$), when the spectrum is dominated in this region by the peculiar, early-type visual companion.

FIGURE 4 (*b*). Enlargements of H and K in a spectrogram showing the visual components of the Antares system. The M star (top) and B star (bottom) were both held stationary on the spectrograph slit. Original dispersion 2.3 A/mm.

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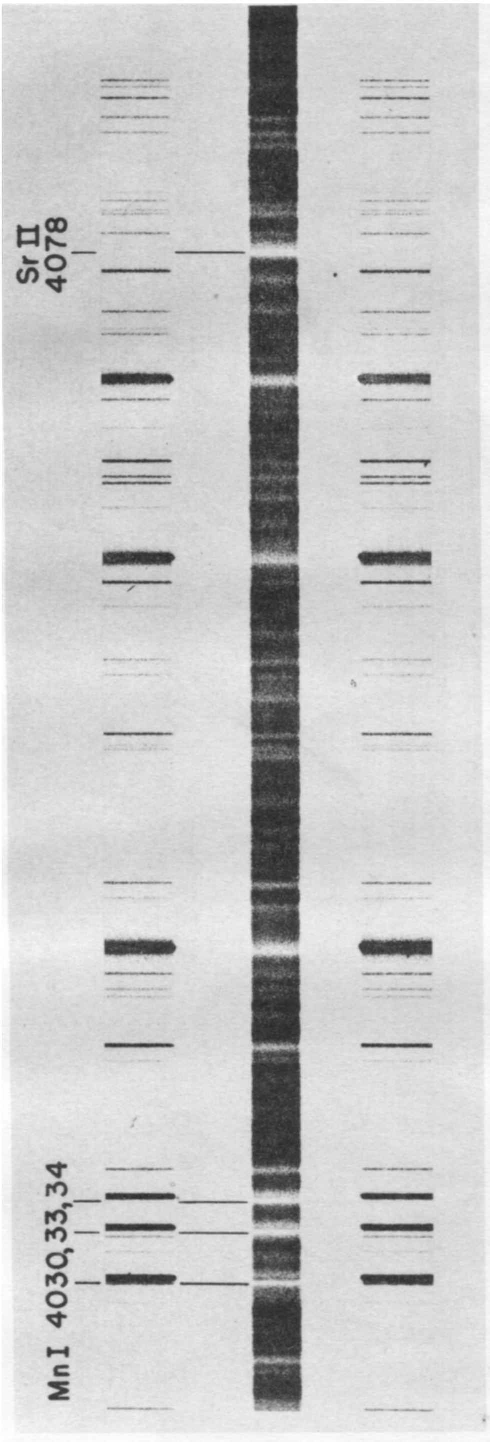

Fig. 1a

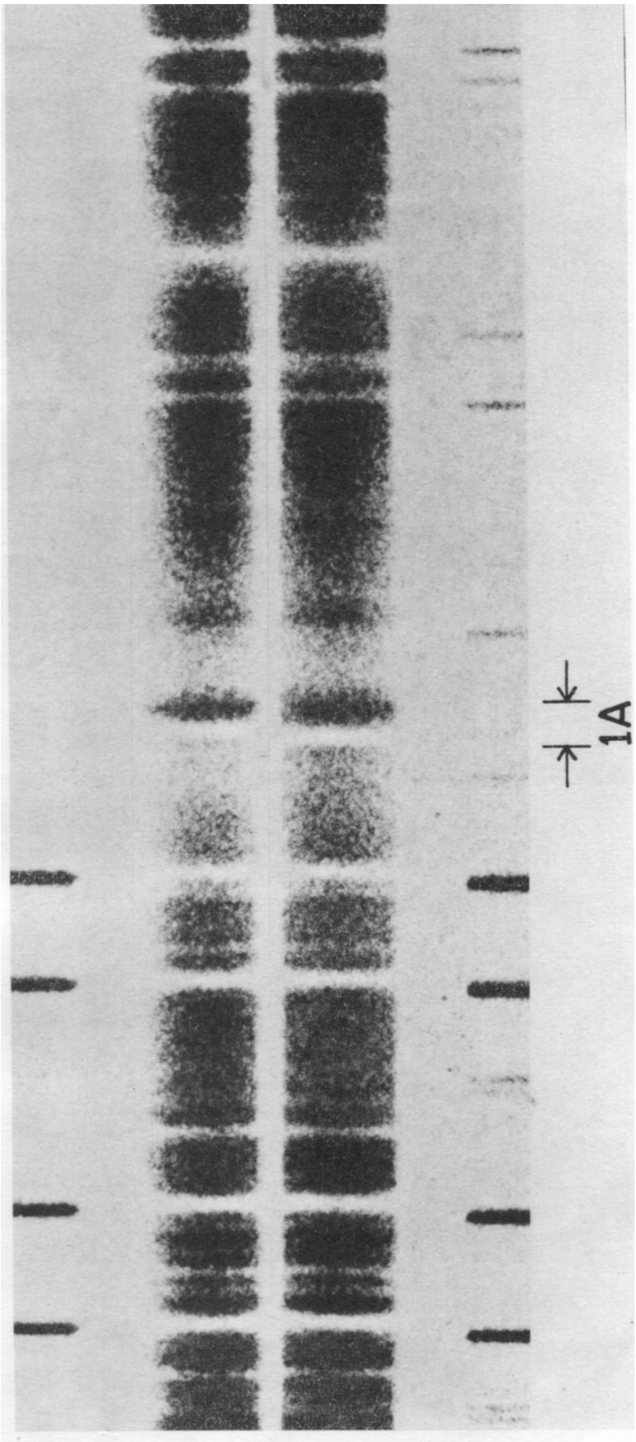

Fig. 1b

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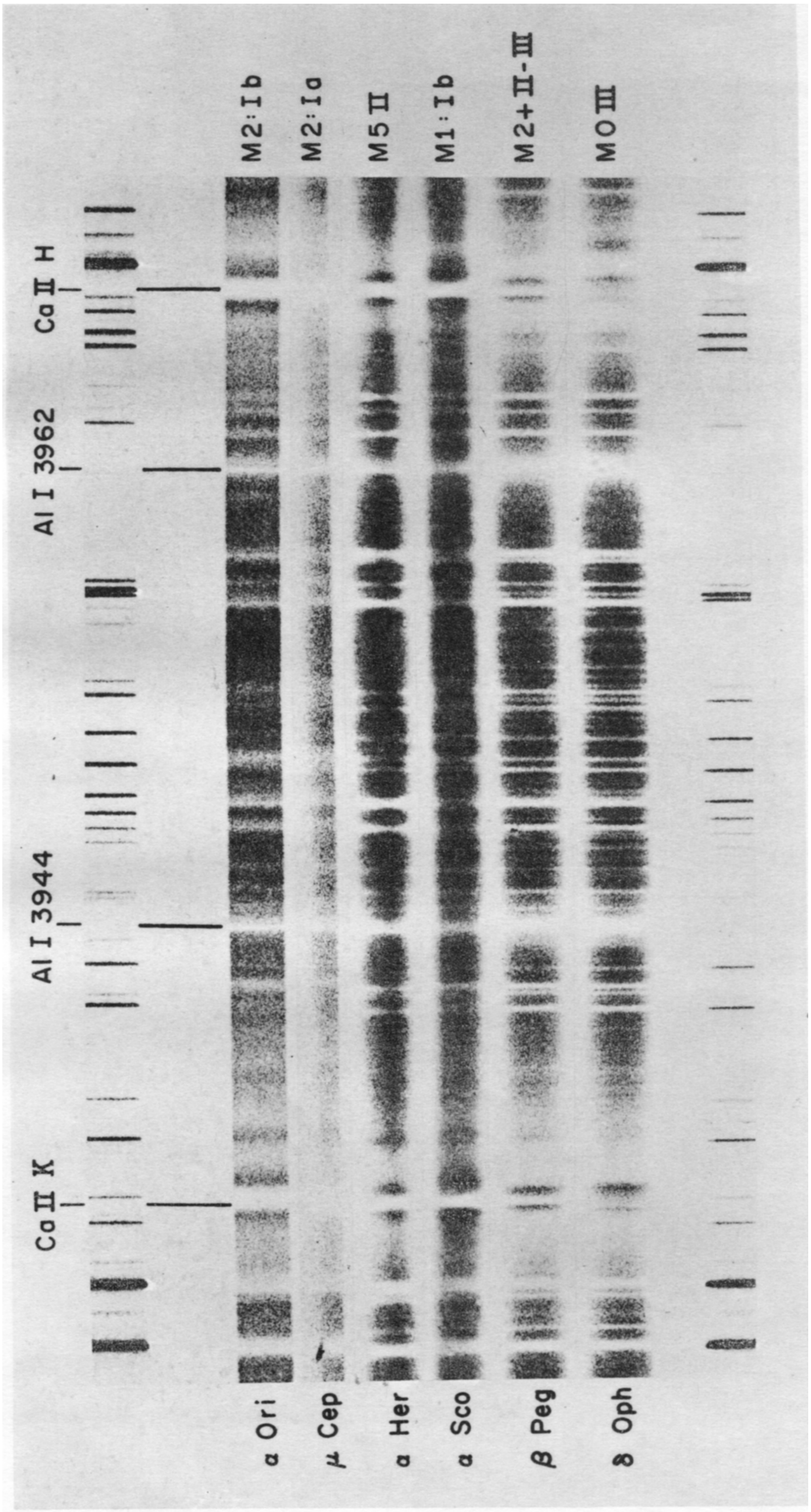
Ca II H
Al I 3962
Al I 3944
Ca II K
M2:Ib
M2:Ia
M5 II
M1:Ib
M2+II-III
M0 III
α Ori
μ Cep
α Her
α Sco
β Peg
δ Oph

Fig. 3

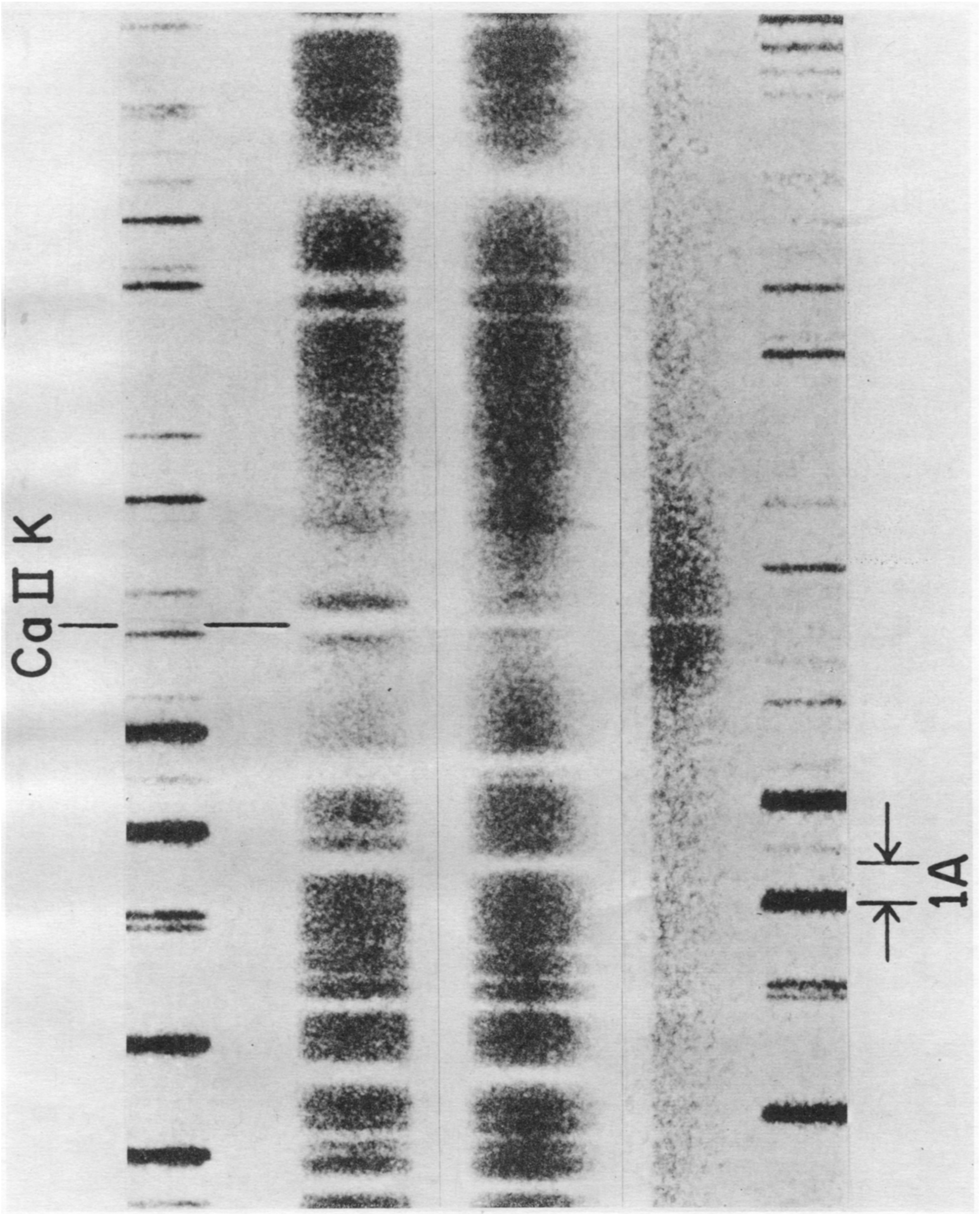

Fig. 4a

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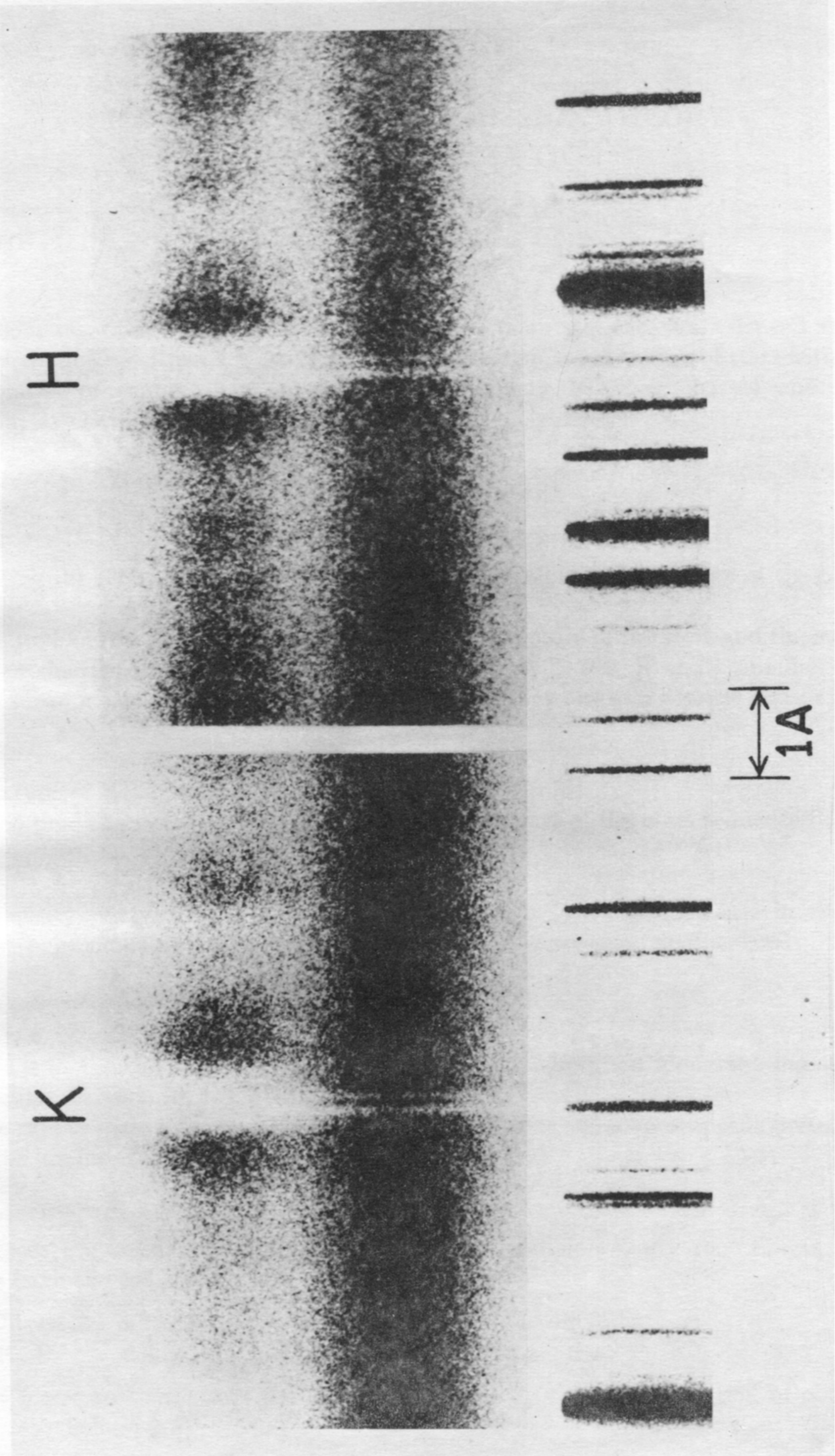

Fig. 4b

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