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EVOLUTION OF STARS WITH SUPPRESSED CORE CONVECTION

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ABSTRACT

Stellar evolution on the upper main sequence has been computed for models of stars with cores assumed to be in radiative equilibrium, up to the point of central helium ignition. The role of the Schönberg-Chandrasekhar limit for an isothermal core is found to be critical for the evolutionary tracks. Observational data are used to rule out the hypothesis of evolution with radiative cores (in upper main-sequence stars) and, by implication, of magnetic fields that are sufficiently strong to have suppressed the core convection.

I. INTRODUCTION

Modern models of stars on the upper main sequence contain convective cores if the usual Schwarzschild criterion is used to test for convective instability. Gough and Tayler (1966) have derived a modified criterion, valid when a magnetic field is present, which indicates that convection is suppressed when the vertical magnetic pressure is comparable with the gas pressure. In that case, the large magnetic field has to be included explicitly in the basic equations of stellar structure. However, if the magnetic pressure in the core is much smaller than the gas pressure ($\sim 10^{17}$ dyne cm^{-2}) but still appreciably larger than the turbulent pressure ($\sim 10^{8}$ dyne cm^{-2}), the magnetic field may possibly cut down the efficiency of convection so much that energy is transported mostly by radiation without having any other important effect. Since convection cannot generate a magnetic field whose pressure is larger than the turbulent pressure itself, we may suppose that the hypothetical magnetic field is of "fossil" origin (Cowling 1965).

In the present paper, the evolution of upper main-sequence stars is investigated under the assumption of a completely radiative interior (§ II). Whether or not a moderate magnetic field can induce such an effect (see the arguments pro and con by Moss and

Tayler [1969, 1970]), other (unknown) mechanisms may., In a similar spirit, Fowler (1972) has offered the opposite suggestion that an ostensibly stable radiative core may become convective for unknown reasons. In our case at least, the resulting stellar models are amenable to an immediate and decisive comparison with observational data (§III).

II. THEORETICAL MODELS

Stellar models with suppressed convection have been constructed for masses of 5, 7, 10, 15, 30, and 60 $M_\odot$ from the zero-age main sequence (ZAMS) to the onset of core helium burning. The initial chemical composition was chosen to be $X_e = 0.739$ and $Z_e = 0.021$. The stellar-evolution program and the physical input data used in constructing the models have been described elsewhere (Stothers and Chin 1973). Moss and Tayler (1970) have already constructed a ZAMS model with suppressed convection for a mass of 1.5 $M_\odot$.

Our main results are given in Table 1 for five critical stages of evolution at each mass: (1) the ZAMS, (2) the stage of minimum effective temperature during core hydrogen burning, (3) the subsequent stage of maximum effective temperature, (4) the stage of maximum mass fraction contained in the isothermal helium core, and (5) the stage of onset of core helium burning. In the table, X_c is the central hydrogen content and q_s is the mass fraction of the peak of nuclear energy generation.

Throughout the mass range 1-60 $M_\odot$ (see, e.g., Iben [1967] for 1 $M_\odot$), the evolutionary behavior of stars with radiative cores is very similar. Evolution proceeds nearly vertically on the H-R diagram (fig. 1) until the inner helium core reaches a critical mass. Thereupon a rapid radius expansion takes place, which lowers the effective temperature because the surface luminosity remains nearly constant. This scheme of evolution with a radiative core gives the shortest possible lifetime (because the core mass is very small) and therefore is to be contrasted with those schemes which have very large core masses or even yield a completely mixed evolution (see Stothers 1970).

Although the exterior evolutionary features of our models bear a qualitative resemblance to those of models having convective cores (Stothers 1972a), the interior evolution is rather different. On the ZAMS, radiative core temperatures are high because the superadiabatic temperature gradient near the center is very steep. Expansion of the central regions causes a shallow density inversion to develop initially, but, when $X_c \approx 0.2$, the peak of nuclear energy production shifts from the center to a thick surrounding shell. Apparently as a result of the purely radiative transport of energy, the central and surface temperatures are found to be inversely correlated. For stellar masses less than 30 $M_\odot$, the minimum effective temperature attained during central hydrogen burning occurs when X_c is still appreciable, but the subsequent maximum of effective temperature occurs long after the exhaustion of central hydrogen.

During the slow phase of outward growth and thickening of the hydrogen shell source, the helium core becomes more massive and more nearly isothermal, until a limiting mass fraction q_{SC} is reached (Schönberg and Chandrasekhar 1942). When this limit is exceeded, a rapid contraction of the helium core ensues. The new (gravitational) energy supply re-establishes a temperature gradient in the core, and the central temperature rises at an accelerated pace. The increased flow of energy through the hydrogen shell steepens the local temperature gradient and the shell grows rapidly narrower. It is interesting that the existence of the Schönberg-Chandrasekhar limit for an isothermal core is confirmed over a large range of stellar masses, although q_{SC} diminishes slightly at higher masses from its value of ~ 0.10 in solar-mass stars, because of the broader mass fraction over which hydrogen burns at higher masses (see fig. 2).

For the three masses 5, 15, and 60 $M_\odot$, evolutionary calculations were continued into the phase of core helium depletion. Because of the steep hydrogen profile across the shell source and the nearly flat hydrogen profile above it, this phase began when the star was still in the blue-giant configuration (see Stothers and Chin 1968). At 5 and 15 $M_\odot$, a thermal runaway in the nondegenerate helium core was encountered, and the calculations were terminated after 2 per cent of the central helium had been depleted. In the last models calculated, the central temperature was increasing at a rate of $\sim 1\ ^\circ\mathrm{K\ sec}^{-1}$. The runaway seems to be due to the large flux generated near the center, all of which must be carried by slow radiative processes (effectively bottling up the flux) since convection has been suppressed. At 60 $M_\odot$, a thermal runaway did not appear in the core, and the evolution was followed to the stage of central helium exhaustion; the evolutionary track on the H-R diagram remained practically a stationary point, as was to be expected since the hydrogen profile above the shell is nearly flat (Stothers and Chin 1968). Earlier stages of evolution were not tested for thermal instability of the hydrogen-burning layers, but it is quite possible that the hydrogen-burning shell is thermally unstable, given its deep location, thick mass, and steep hydrogen profile (see Stothers and Chin 1972).

III. COMPARISON WITH OBSERVATIONS

Along the ZAMS, stellar models with radiative cores have slightly fainter luminosities and cooler effective temperatures than do stellar models with convective cores, and therefore the location do stellar models with convective cores, and therefore the location of the ZAMS on the H-R diagram is about the same for the two cases. Since the total evolutionary rise in brightness during the slow stages of hydrogen burning differs between the two cases by <0.1 mag at 5 $M_\odot$ and by only 0.4 mag at 60 $M_\odot$, no meaningful discrimination can be effected on the (mass, luminosity) — plane, where the typical observational uncertainty is about 0.5 mag (Stothers 1972a, fig. 3).

Four other comparisons with observational data, however, seem definitely to rule out the radiative cores. First, the evolutionary change in effective temperature during the slow stages of hydrogen burning is much smaller for models with radiative cores ($\Delta \log T_e < 0.02$) than for models with convective cores ($\Delta \log T_e > 0.06$), over the mass range 5-60 $M_\odot$. In the former case, the expected spread in spectral type at a given mass is only about half a decimal subclass, which is considerably smaller than the spread actually observed in the (mass, spectral type)— plane for upper main-sequence stars (Stothers 1972a, fig. 2). Second, the turnup of the main sequence in the H-R diagram for a young cluster, assuming coeval star formation, would be expected to to be a diagonal strip for radiative cores, not a vertical strip as is actually observed. Third, it seems likely that, for all moderate to heavy stellar masses, the phase of core helium depletion will occur at nearly constant effective temperature if the core is radiative. But this is observationally ruled out by the wide distribution of spectral types found among the supergiants of a given luminosity (Stothers 1972a, fig. 4). Fourth, as a general rule, theoretical models of mass exchange in a close binary system where the primary makes contact with its Roche lobe after the end of core hydrogen burning indicate that this component loses nearly all of its hydrogen envelope. Had the core always been radiative, the predicted mass for a binary remnant would be relatively small, and therefore probably in contradiction to the large masses actually observed in relevant binary systems (e.g., β Lyr, μ^1 Sco, and V356 Sgr), with which the assumption of a convective core seems to be in accord (Stothers 1972a, b). Most other observed binary systems that have exchanged mass have probably done so before the original primary finished core hydrogen burning, and so the masses of the primary remnants in these systems would not reflect their initial core masses in any obvious way (Ziółkowski 1969).

Suppression of core convection in upper main-sequence stars seems, therefore, to be an invalid assumption, regardless of whether or not a magnetic field is present. Two arguments against a strong magnetic field within the core have previously been suggested, namely, the observed smallness of the Zeeman effect in the spectra of a few known, recently formed binary remnants, e. g., β Lyr and

V356 Sgr (Stothers 1972b), and the unobserved geometrical distortion of the components of wide (tidally undistorted) eclipsing binary systems (as implied by the remarks of Moss and Tayler 1970). Even the strong magnetic fields inferred in pulsars (e.g., Chiu 1970) imply, under the usual assumption of magnetic flux conservation, fields of only hundreds of gauss in the cores of initial main-sequence stars. We conclude that inclusion of magnetic fields (except possibly for their interaction with rotation) in models for normal upper main-sequence stars does not seem to be required by the available observational data.

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REFERENCES

Chiu, H. - Y. 1970, Pub. A. S. P., 82, 487.

Cowling, T. G. 1965, in Stellar Structure, ed. L. H. Aller and D. B. McLaughlin (Chicago: University of Chicago Press), p. 425.

Fowler, W. A. 1972, Nature, 238, 24.

Gough, D. O., and Tayler, R. J. 1966, M. N. R. A. S., 133, 85.

Iben, I., Jr. 1967, Ap. J., 147, 624.

Moss, D. L., and Tayler, R. J. 1969, M. N. R. A. S., 145, 217.

__________. 1970, ibid., 147, 133.

Schönberg, M., and Chandrasekhar, S. 1942, Ap. J., 96, 161.

Stothers, R. 1970, M. N. R. A. S., 151, 65.

__________. 1972a, Ap. J., 175, 431.

__________. 1972b, Nature (Physical Science), 238, 5.

Stothers, R., and Chin, C. - w. 1968, Ap. J., 152, 225.

__________. 1972, ibid., in press.

__________. 1973, ibid., to be published.

Ziółkowski, J. 1969, Ap. Sp. Sci., 3, 14.

TABLE 1

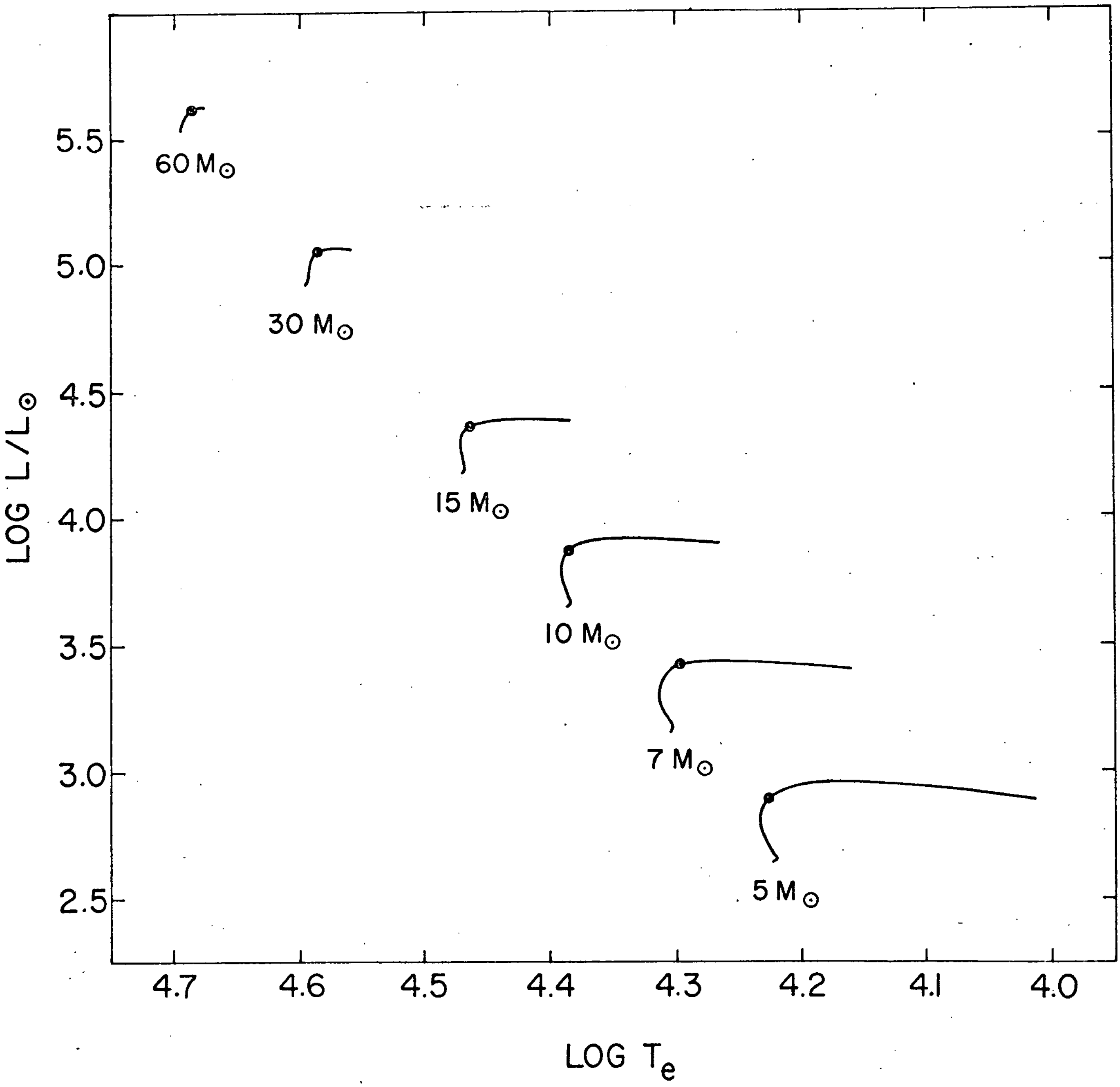
EVOLUTIONARY SEQUENCES WITH SUPPRESSED CORE CONVECTION

$M/M_{\odot}$	Stage	X_c	log T_c	log P_c	q_s	log$(L/L_{\odot})$	log T_e	$\tau(10^6$ yr)
5	1	0.739	7.490	1.046	0	2.659	4.221	0
	2	0.406	7.496	1.163	0	2.662	4.219	1.69
	3	0	7.451	2.000	0.05	2.815	4.232	48.58
	4	0	7.460	2.375	0.09	2.897	4.226	74.89
	5	0	8.004	4.264	0.10	2.893	4.012	76.62
7	1	0.739	7.523	0.835	0	3.168	4.303	0
	2	0.390	7.528	0.961	0	3.172	4.302	0.92
	3	0	7.485	1.796	0.05	3.314	4.313	21.41
	4	0	7.521	2.579	0.09	3.429	4.295	28.61
	5	0	8.003	4.087	0.10	3.411	4.161	29.92
10	1	0.739	7.552	0.628	0	3.668	4.385	0
	2	0.303	7.557	0.798	0	3.674	4.383	0.73
	3	0	7.520	1.602	0.05	3.803	4.392	9.90
	4	0	7.531	2.084	0.09	3.879	4.384	14.04
	5	0	8.047	3.845	0.10	3.912	4.264	14.48
15	1	0.739	7.577	0.411	0	4.182	4.470	0
	2	0.185	7.582	0.656	0	4.195	4.468	0.71
	3	0	7.557	1.288	0.05	4.288	4.472	4.47
	4	0	7.576	1.974	0.08	4.373	4.463	6.19
	5	0	8.090	3.673	0.09	4.393	4.385	6.56
30	1	0.739	7.605	0.087	0	4.928	4.595	0
	2	0.020	7.612	0.572	0.02	4.968	4.592	1.01
	3	0	7.608	0.736	0.03	4.985	4.592	1.33
	4	0	7.624	1.740	0.08	5.061	4.584	2.49
	5	0	8.073	3.251	0.08	5.073	4.558	2.57
60	1	0.739	7.622	-0.183	0	5.527	4.694	0
	4	0	7.678	1.525	0.07	5.623	4.685	1.45
	5	0	8.157	3.115	0.06	5.628	4.677	1.50

FIGURE CAPTIONS

Fig. 1. - Theoretical H-R diagram showing evolutionary tracks for models of stars with suppressed core convection, from the ZAMS to the onset of core helium burning. A dot indicates the stage at which the Schönberg-Chandrasekhar limit for the core mass is reached.

Fig. 2. - Hydrogen profiles for stellar models of 5 $M_\odot$ (solid lines), 15 $M_\odot$ (dash-dot lines), and 60 $M_\odot$ (dashed lines), with suppressed core convection. The evolutionary stages represented are: (1) $X_c \approx 0.4$; (2) $X_c \approx 10^{-5}$; and (3) $X_c = 0$ (at the Schönberg-Chandrasekhar limit for the core mass).



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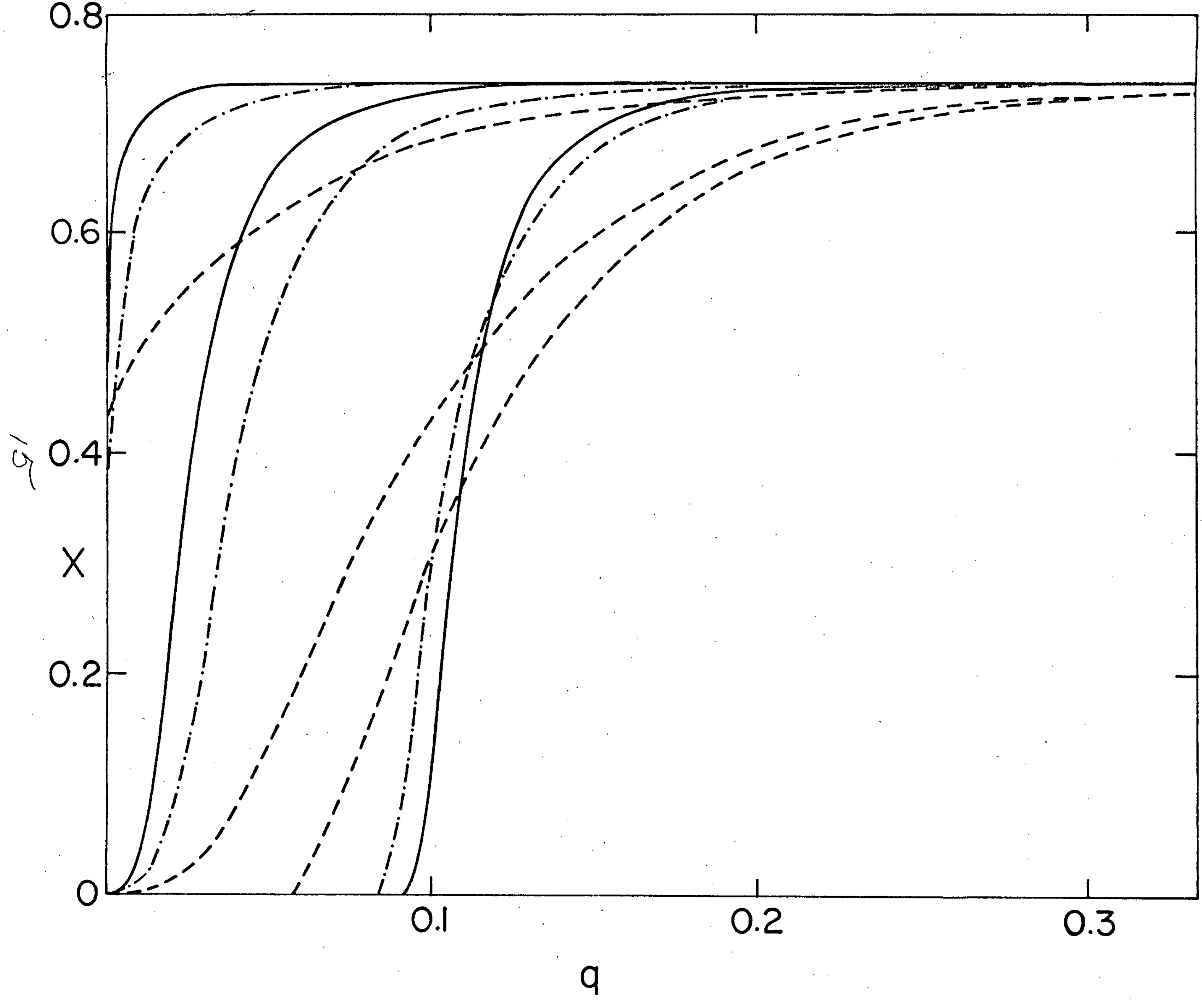
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