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Thermal Blooming in the Transsonic Regime

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FOR THE COMMANDER

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THERMAL BLOOMING IN THE TRANSSONIC REGIME

L.C. BRADLEY

Group 51

PROJECT REPORT LTP-24
(Laser Technology Program)

30 JANUARY 1974

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ABSTRACT

Quantitative estimates are given for the phase changes caused by heating of the atmosphere by a laser beam slewing at transsonic velocities. It is shown that for a beam slewing from near rest relative to the atmosphere, the transsonic effect is negligible; but for a beam transmitted from an aircraft, it can be important.

THERMAL BLOOMING IN THE TRANSSONIC REGIME

It is well known that when the free-stream velocity of a flow is close to Mach 1, large density changes can be induced by comparatively small perturbations in the flow. It has been suggested[1] that these density changes can have a serious effect on the thermal blooming of a high-power laser beam. In this note I attempt a quantitative assessment of this problem.

Consider a slewed laser beam, so that the effective transverse free-stream wind velocity (taken to be in the positive x-direction) is a linear function of z, the axial coordinate. Assume that the transverse beam dimensions and the transverse wind velocity change slowly with z, and that the system has attained a steady state. (The latter assumption is an unrealistic one, since steady state is achieved very slowly near Mach 1: the sound waves move slowly upstream relative to the perturbations. Nevertheless the calculation should give an upper limit, which is all I wish to attain in this note.) Then the hydrodynamics may be taken to be locally two-dimensional. For this situation one may use the Green's function found by Tsien and Beilock[2] for heat deposition in a uniform flow, using the hydrodynamic equations linearized around the free-stream velocity, for both subsonic and supersonic regimes. Using these expressions, and the assumption that the heat deposition per unit volume is αI, where I is the beam irradiance and α the absorption coefficient, the density change in the subsonic regime may be written as

$$\Delta\rho(x,y) = -\frac{(\gamma-1)M\alpha}{2\pi c^3\sqrt{1-M^2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{I(x',y')(x-x')\,dx'\,dy'}{(x-x')^2+(1-M^2)(y-y')^2}$$

$$-\frac{\gamma-1}{Mc^3}\int_{-\infty}^{x} I(x',y)\,dx' \quad .$$

Here M is the free-stream Mach number and c is the free-stream sound velocity. A sign error in Ref. 2 has been corrected. In the supersonic regime the density change is

$$\Delta\rho(x,y) = \frac{(\gamma-1)\alpha}{2c^3\sqrt{M^2-1}} \int I(x',y')\,ds - \frac{\gamma-1}{Mc^3}\int_{-\infty}^{x} I(x',y)\,dx' \quad .$$

Here the first term is an abbreviation for two line integrals to be taken along the two characteristics which converge from upstream on the observation point. Thus the first integral may be written in expanded form as

$$\int I(x',y')ds = M\int_{y}^{\infty} I(x-(y'-y)\sqrt{M^2-1}\,,\ y')\,dy'$$

$$+\ M\int_{-\infty}^{y} I(x+(y'-y)\sqrt{M^2-1}\,,\ y')\,dy' \quad .$$

In both expressions for $\Delta\rho$, the second term (the entropy term) is the one that is usually given for small wind velocities, assuming complete pressure relaxation; the first term (the pressure term) arises from acoustic waves generated by the disturbance. It will be seen that the pressure terms in both regimes diverge at $M = 1$, and of course the linearization is no longer valid in the immediate vicinity of this singularity. But the singularity is not a strong one, and presumably gives an upper limit to the pressure effect in the vicinity of $M = 1$. Thus these expressions will serve to estimate the influence of the pressure terms on optical propagation.

In optical propagation the important quantity is not $\Delta\rho$ itself, but the induced phase change, which is proportional to $\int \Delta\rho \, dz$. With M a linear function of z, this integral does not diverge, even when one of the limits corresponds to $M = 1$. In order to estimate the relative importance of the pressure and entropy terms, numerical integrations have been performed assuming a Gaussian beam intensity profile, $I = I_o \exp(-r^2/a^2)$, for points along the centerline of the beam, and for various intervals of M. A Gaussian was chosen because part of the integration can be done analytically.

The results are presented in Figs. 1-6. The contributions from the pressure and entropy terms are shown separately, as well as their sum, for ease of comparison. The ordinate is given in arbitrary units, but the scale is the same for all of the figures. It will be seen that near $M = 1$ the pressure term predominates, with total phase-change gradient as much as an order of magnitude greater than that given by the entropy term alone. It should be pointed out however that the latter term corresponds to an effective wind speed of about 330 m/sec in the atmosphere, and that the range of z over which the pressure predominates may be comparatively small. Thus for a beam slewing from rest, the region near the transmitter, influenced mainly by the much smaller natural wind velocities, will be much more important for blooming than the transsonic region. On the other hand, a beam transmitted from an aircraft flying near Mach 1 could be severely affected, particularly if the slewing rate were small. More exact evaluation of this effect would require a difficult computation using time as well as three space variables.

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2. H. S. Tsien and M. Beilock, J. Aero. Sci. 16, 756 (1949).

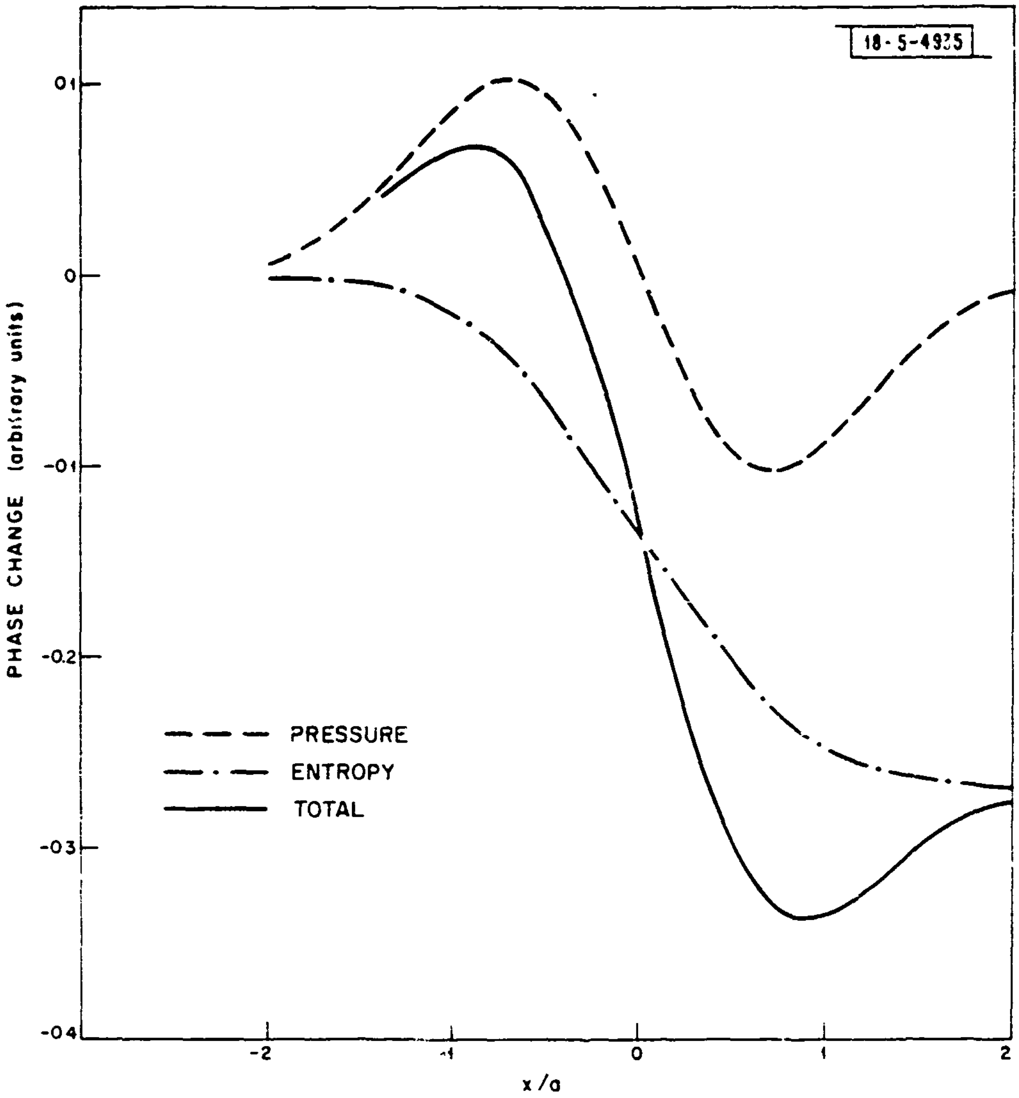

Fig. 1. Contributions to total phase change on centerline of a Gaussian beam. M = 0.7 - 0.8

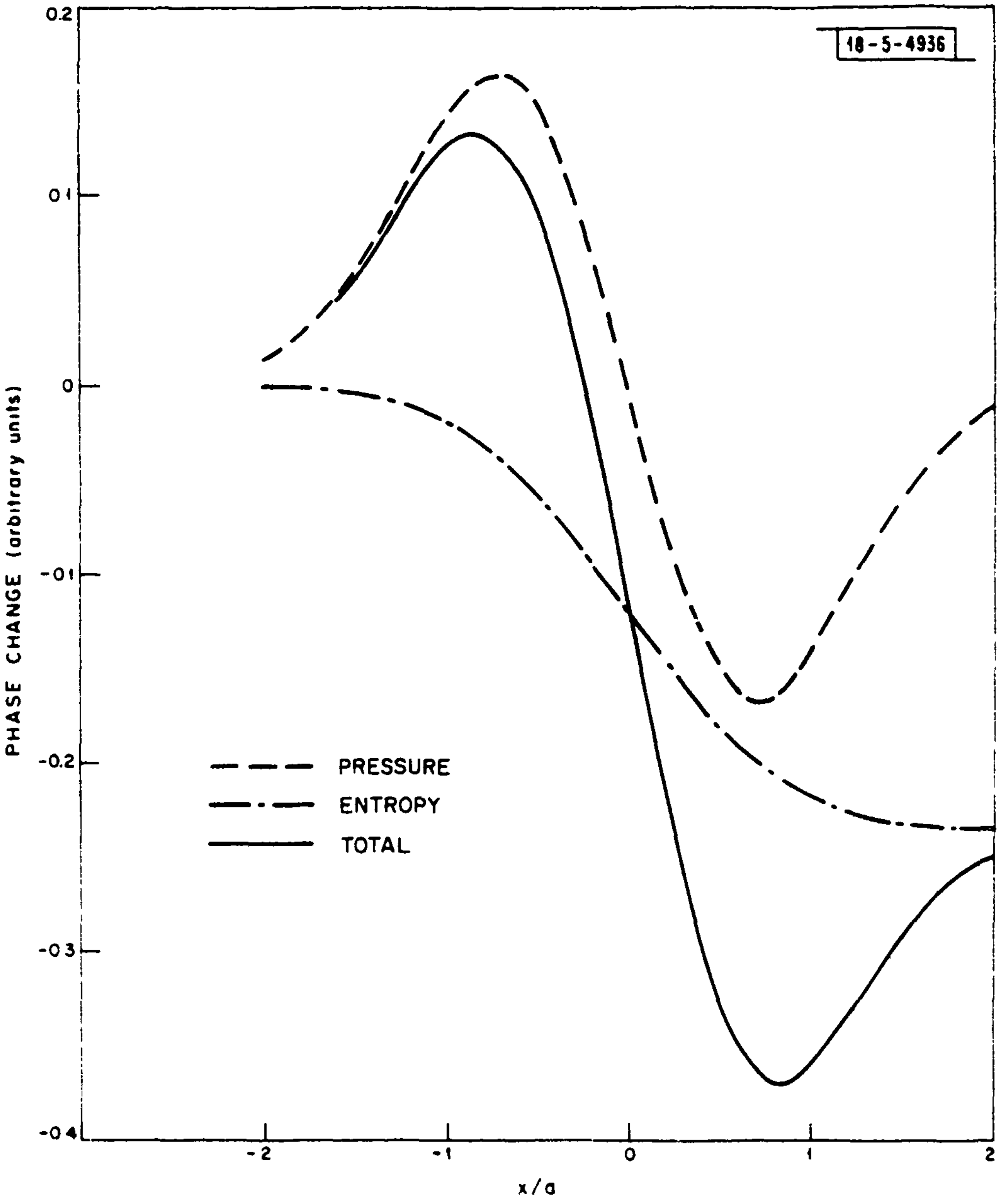

Fig. 2. Contributions to total phase change on centerline of a Gaussian beam. M = 0.8 - 0.9

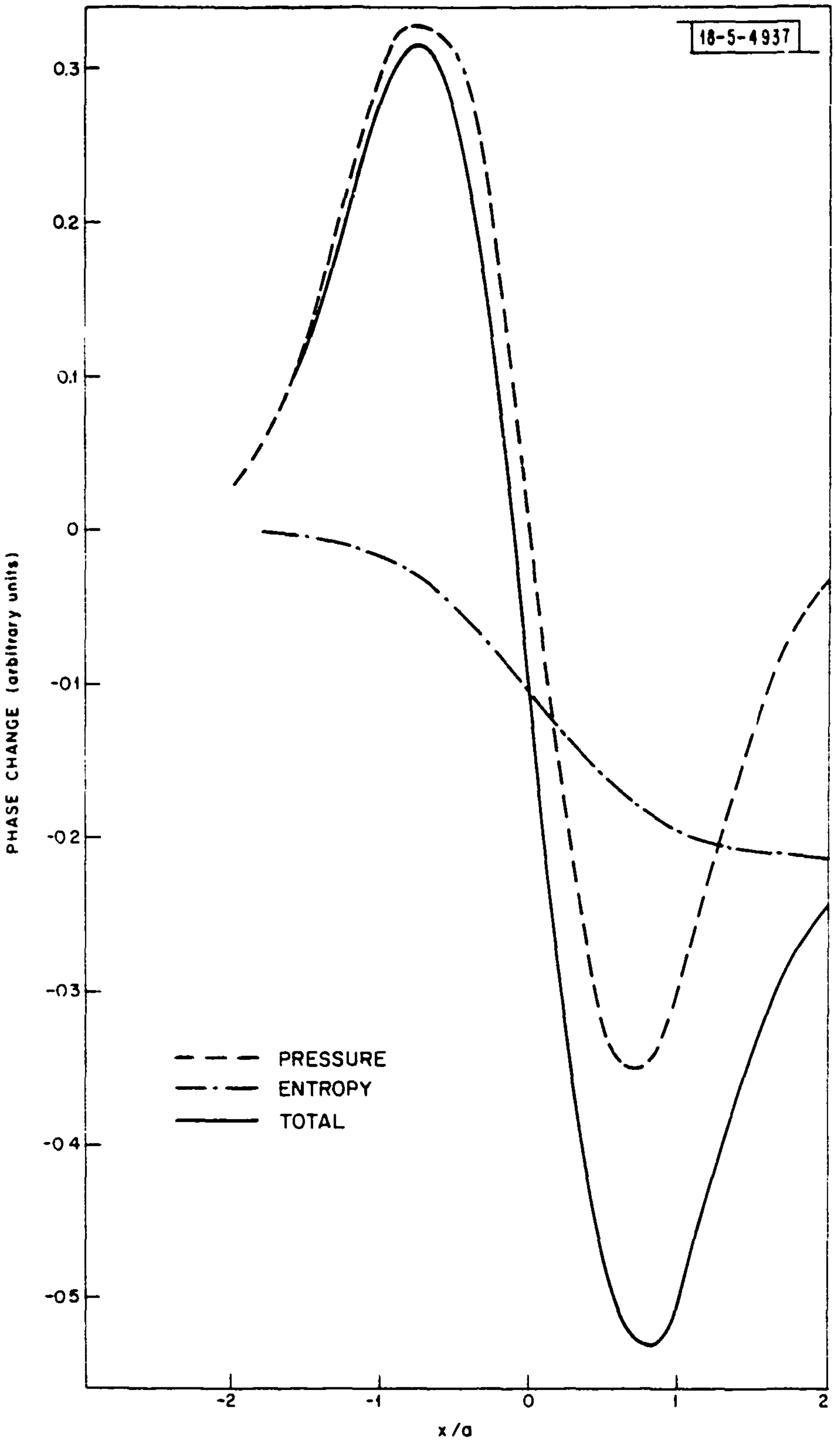

Fig. 3. Contributions to total phase change on centerline of a Gaussian beam. M = 0.9 - 1.0

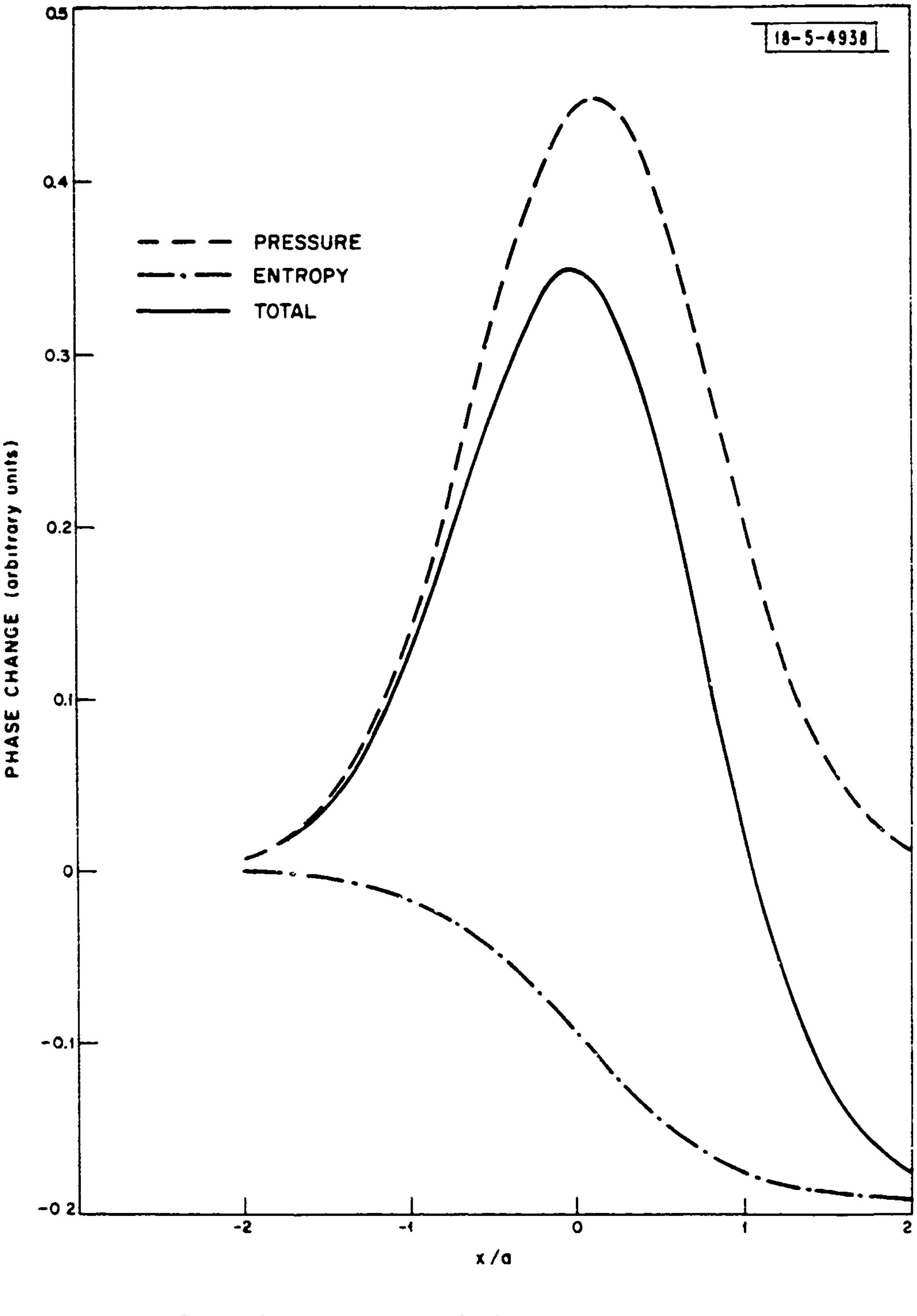

Fig. 4. Contributions to total phase change on centerline of a Gaussian beam. M = 1.0 - 1.1

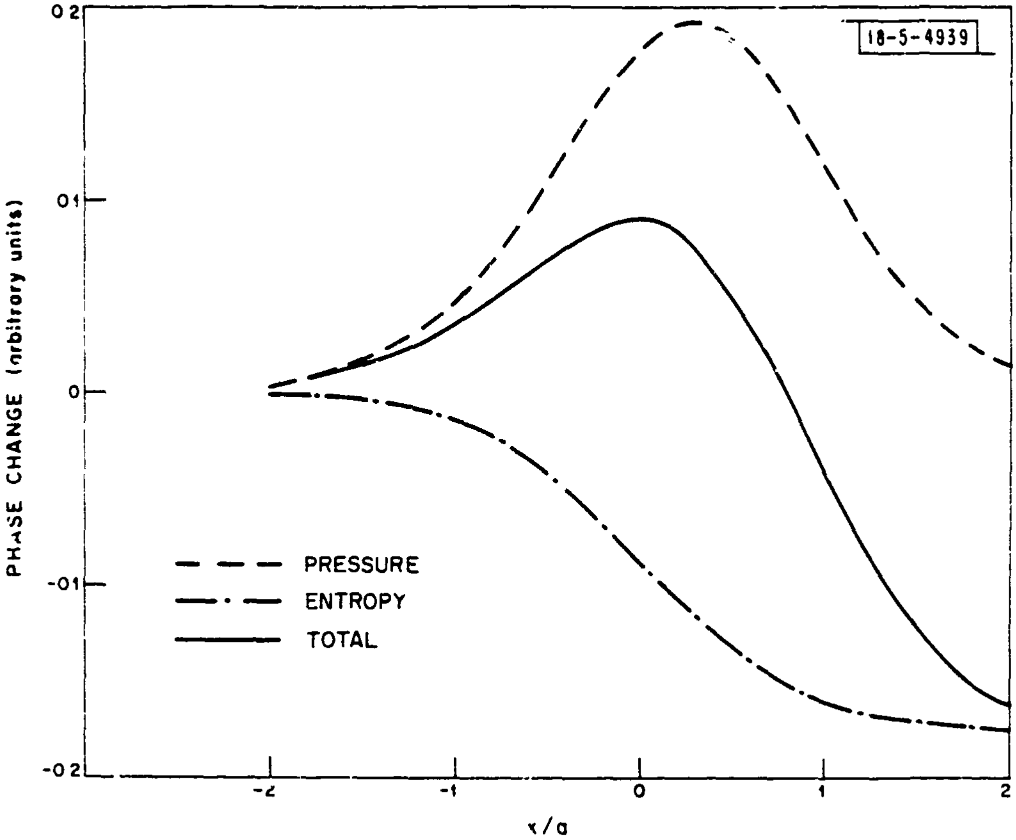

Fig. 5. Contributions to total phase change on centerline of a Gaussian beam. M = 1. 1 - 1. 2

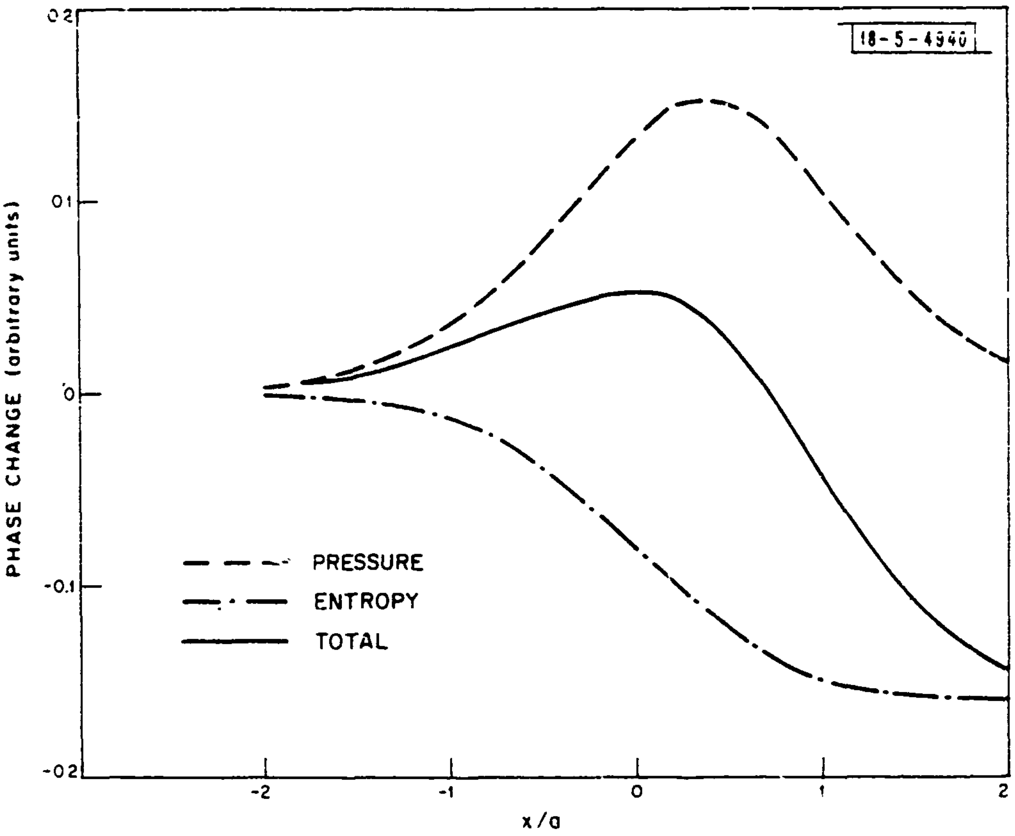

Fig. 6. Contributions to total phase change on centerline of a Gaussian beam. M = 1.2 - 1.3

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