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THE PHARO CODE.(U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The PHARO code predicts the visible and infrared radiative output of high altitude nuclear bursts. Using the results of the large scale NRL hydrocodes, both the spatial and temporal variation of the radiation (watts/cm^2sr) in arbitrary wavelength intervals is determined. The results are a series of "isophot" plots for arbitrarily placed cameras or sensors which can be directly compared with experiment. In addition to monitoring the important line and band transitions the bound-bound, free-bound, and free-free radiation is calculated for a recombining oxygen plasma. In particular, the bound-bound

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20. ABSTRACT (Continued)

radiation does not assume a Saha population of excited levels but calculates this radiation as a function of electron temperature and density and ground state oxygen density. Comparisons with representative high altitude data are exhibited.

CONTENTS

THE PHARO CODE

SECTION I

INTRODUCTION

PHARO, an acronym for "Phenomenology and Radiation Output," is a computer code developed to calculate the visible and infrared (IR) emission from a disturbed atmosphere. As part of NRL's high altitude nuclear effects (HANE) program, it utilizes the results of NRL's high altitude phenomenology calculations, specifically the MRHYDE (and its successor, PHOENIX) computer code. It is currently being used, also, to study LWIR emission from plasma cloud releases, using codes which model the development of spatial irregularities in the high altitude atmosphere. PHARO calculates emission in the visible and IR from all sources of radiation including:

(1) bound-bound transitions in the decaying atomic plasma and transitions from the low lying metastable states of atoms and atomic ions,

(2) band emission from molecules due to electron impact excitation or heavy particle reactions, which leave a product species in an excited electronic or vibrational state (e.g., chemiluminescence),

(3) free-bound and free-free continuum transitions.

A detailed description of these lines and bands is given in Section II.

The output of the PHARO code consists of contour plots of radiative intensity (watts/cm^{2}ster) or "isophot" plots for arbitrarily placed sensors. These will be described in more detail in Section III. A series of these plots give both a spatial and

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temporal picture of the radiation, which is directly comparable with experiments. In Section IV we present a comparison between PHARO results and some measured values, and a discussion of further potential comparisons.

Briefly, PHARO works as follows: the calculation of the radiation starts with the results of a computer code such as MRHYDE, a three-dimensional, two fluid MHD reactive flow code which describes both the hydrodynamics and chemistry of the high altitude burst. MRHYDE begins its calculations on the order of one second after burst, using as initial conditions the atmosphere after prompt x-ray emissions and deposition of uv energy, debris energy, and inclusion of a blast wave.

The PHARO code reads from tape the MRHYDE results at prespecified times and at a large number of mesh points. For the results we will present in this report, there were of order 10^4 mesh points (due to reflection symmetry about a vertical plane through the magnetic field there are effectively twice this number).

This report will describe PHARO II which differs from PHARO I[1] primarily in the treatment of the bound-bound radiation. In PHARO I the calculations assumed a hydrogenic recombining plasma with Saha populations of the excited states. In PHARO II an oxygen plasma is assumed and actual population densities of the excited states are calculated.[2]

SECTION II

HANE RADIATIVE EMISSION CALCULATIONS

The species carried in the MRHYDE code are given in Figure 1. The temperatures listed are the electron temperature, T_e, the vibrational temperature of N_2, T_v, and the heavy particle kinetic temperature, T_a. Some of the HANE codes currently carry separately the ion temperature, T_i, and the neutral temperature, T_n. N_2^+ is not carried in MRHYDE since it is generally a minor ion by the time the MRHYDE calculations are initiated. It is carried in the uv deposition code which provides initial conditions for MRHYDE, however. In Figure 2 we exhibit the major line emissions from metastable states and molecular bands that the PHARO code monitors. It is apparent that not all of the excited state species that we require for PHARO are carried in MRHYDE. Those not carried we assume to be in quasi-steady state equilibrium and calculate their populations. The species for which this assumption is used are $N(^2P)$, $O(^1S)$, $N^+(^1S)$, $O^+(^2D)$, $O^+(^2P)$, $O_2(a^1\Delta)$, and $O_2(b^1\Sigma)$.

To calculate the NO chemiluminescence in the fundamental at 5.3μ and the overtone at 2.7μ the following assumptions were used. The vibrationally excited NO, formed via the reaction $N + O_2 \rightarrow NO + O$, is sufficiently exothermic to populate NO up to the 6th vibrational state. In addition, $N(^2D) + O_2 \rightarrow NO + O$ can excite up to the 18th vibrational level of NO. We assume half the exothermicity is available to vibrational states. A straight-forward steady state calculation then gives the number of photons of the fundamental and overtone for these reactions. Since quenching has not been included, this will give an upper limit to the emitted radiation. Also, we include the translation-vibration reaction between NO and hot O atoms which is frequently a critically important source of 5.3μ and 2.7μ radiation. In some applications more sophisticated models have been used for determining the number of photons/reaction.

In a similar way the NO^+ radiation from vibrational transitions at 4.3μ and 2.15μ are calculated[3] assuming formation of vibrationally excited NO^+ via $N^+ + NO \rightarrow N + NO^+$, $N + O_2^+ \rightarrow NO^+ + O$, $N_2 + O^+ \rightarrow NO^+ + N$, $N^+ + O_2 \rightarrow NO^+ + O$. In addition, the N_2^+ Meinel Bands are assumed to arise [3] via $N_2 + O^+(^2D) \rightarrow N_2^+(A^2\pi, v = 1) + O$ and the second negative of O_2^+ in the visible is assumed[3] to result from $O^+(^2D) + O_2 \rightarrow O_2^+(A^2\pi) + O$. Finally, a model for the 4.3μ and 10.6μ radiation from CO_2 is included.

To calculate the late-time atomic bound-bound line radiation PHARO II assumes the late-time disturbed atmosphere to be a decaying oxygen plasma. Calculation of the radiation requires a knowledge of the population of the excited states of oxygen as a function of electron density and temperature and, for sufficiently high temperature, the ground state population, $O(^3P)$. To accomplish this a model[2] has been developed which determines the population densities of all triplet and quintet oxygen levels up to n = 18 as a function of these parameters. These calculations have been performed for 11 electron temperatures ranging between .03 and 2.0 eV, 7 electron densities between 10^6 and $10^{12} cm^{-3}$, and, in the case of electron temperatures equal to or greater than .5 eV, the same range of oxygen ground state densities.

The results of the above calculations, the population of 338 excited levels for each of the above set of parameters, are stored on disk. Once wavelength intervals are specified a separate code reads the disk and determines the radiation emitted in each wavelength interval for each set of parameters. These results are, in turn, stored on a disk which is read by the PHARO code for interpolation to the actual temperature and densities at a given point.

Finally, the continuum radiation, oxygen free-bound and free-free emission, are based on the calculations of Davis and Lewis.[4]

SECTION III

PHARO GEOMETRY

In Figure 3 we display the geometry used in the PHARO code to produce the "isophot" plots. B represents the initial burst position. The X-axis is in the direction of the horizontal component of the earth's magnetic field. The proposed position of the camera or sensor is specified by its distance from the burst point, s, a polar angle relative to the upward vertical direction at the burst, Θ, and an azimuthal angle, Φ, measured relative to the horizontal magnetic field direction. A camera at this position may have an arbitrary orientation relative to the burst point. Two angles specify the direction of the line of sight of the sensor: a polar angle, θ, relative to the burst-sensor line and an azimuth angle, ϕ, (not shown in Figure 3) measured relative to the plane defined by the burst point, the sensor position, and the center of the earth.

Having specified the sensor position and orientation a set of rays is constructed. The first ray is along the line of sight of the sensor (as indicated in Figure 3) and the others are arrayed on a set of equally spaced cones with common apex at the sensor point and common axis along the sensor line of sight. On each cone the rays are equally spaced around the cone. Next, a set of equally spaced points is chosen along each ray, from the sensor to the far side of the MRHYDE mesh. By interpolation between the MRHYDE mesh points and these points the total emission at each point along the rays is determined for each wavelength interval of interest, using an appropriate volume as illustrated in Figure 3. Finally, a summation is performed along each ray and the total radiation (watts/cm^{2}ster) from each ray direction determined. In the present version of the code, PHARO II, the emission is assumed to be optically thin. Furthermore, the code permits attenuation of the radiation as it travels from its source through the ambient atmosphere to the sensor. An atmospheric model has been developed and incorporated into PHARO based on the models of McClatchey at AFGL.

The set of ray directions relative to the sensor line of sight form a two-dimensional polar grid of intensities from which the contour plots are constructed. In some applications of the PHARO code, the rays are arrayed on a rectangular grid and the contour plots are constructed from a two-dimensional rectangular grid. With a PHARO sensor placed where measurements were taken it is possible to construct plots that can be directly compared with experimental isophot plots.

SECTION IV

RESULTS AND DISCUSSION

In Figures 4-8 we exhibit typical PHARO plots predicting the radiance (watts/cm^{2}ster) in the 8-14μ band from a high altitude nuclear burst at successive times following initiation of the MRHYDE calculation (times 0.0, 20.0, 60.0, 100.0, and 140.0 seconds). The camera is a distance of 500 km from the burst with its optic axis passing through the burst point. The ordinate and abscissa give the angle in degrees from the camera axis. Alternate contours are solid lines or dots, with the latter, only, labeled. The numbers at the top of the plot label the radiance values. Reading from left to right, the leftmost value corresponds to contour number 1 which is the smallest radiance value that can be plotted, the middle number to contour number 10, and the rightmost number the inverse of the number of contours per logarithmic decade. Thus, in Figure 4, contour 8 represents a radiance of 1×10^{-5} watts/cm^{2}ster and contour 2 is 1×10^{-8} watts/cm^{2}ster. The Figures 4-8 exhibit clearly the temporal effects: the effect of the hydrodynamics in heating the atmosphere and diffusing the plasma, and the chemistry in reducing the emission.

In Figure 9 we see a measured isophot plot of visible radiation from a high altitude burst (on the right) and the corresponding PHARO prediction. Additional predictions and comparisons with data have been documented in the literature.

We view the PHARO code as a very versatile code particularly useful in providing predictions that are easily compared directly with measurements. Specifically, the high altitude bursts that can be modeled by a MRHYDE (PHOENIX) 3D 2-fluid magnetohydrodynamic code provide a set of measurements that can provide direct tests of our understanding of disturbed atmosphere phenomenology. In the past several years there have been important improvements in our understanding of a variety of these atmospheric phenomena that directly bear on measurements that were made, and that have not been tested by comparison with these results.

Consider the Starfish event. There are a set of isophot plots of visible radiation that have been published for times out to 33.9 seconds of the northern conjugate region from an aircraft. There are similar data from other locations that has not been analyzed. This kind of data is in an ideal form for comparison with PHARO predictions.

In addition, there were IR measurements made with a variety of detectors on each of two aircraft. In many cases data above background were obtained for 10^3 seconds. The measurements include the 1.1 - 3.0μ band (spatial radiometer), 4.8 - 5.5μ band and 2.6 - 2.7μ band (filter photometer), a variety of bands between 1.5 and 2.8μ (filter wheel radiometer), 1.55 - 1.62μ (PbS radiometer), 5.0 - 5.5μ (IR Spectrometer). There are, in addition, a variety of uv, visible, and near infrared measurements made both from aircraft and ground stations. The reliability, extent, and state of analysis of this large quantity and variety of data require evaluation. But, in principle, PHARO predictions make these measurements directly accessible to analysis.

ACKNOWLEDGMENT

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N_2, O_2, NO

O_2^+, NO^+

$N, N(^2D), N^+$

$O, O(^1D), O^+$

T_e, T_v, T_a

Fig. 1 — Chemical species and temperatures carried in MRHYDE (and PHOENIX) 3D hydrocode

PHARO II

PHENOMENOLOGY AND RADIATION OUTPUT CODE

OPTICAL AND IR TRANSITIONS

O	6300Å, 5577Å
N	5200Å, 1.04μ
N^+	6527Å, 5754Å
O^+	7320Å
N_2^+	3914Å, 9212Å, 1.5μ
O_2	7619Å, 1.26μ
NO	2.7μ, 5.4μ
NO^+	2.15μ, 4.3μ

Fig. 2 — Important visible and infrared transitions monitored in PHARO

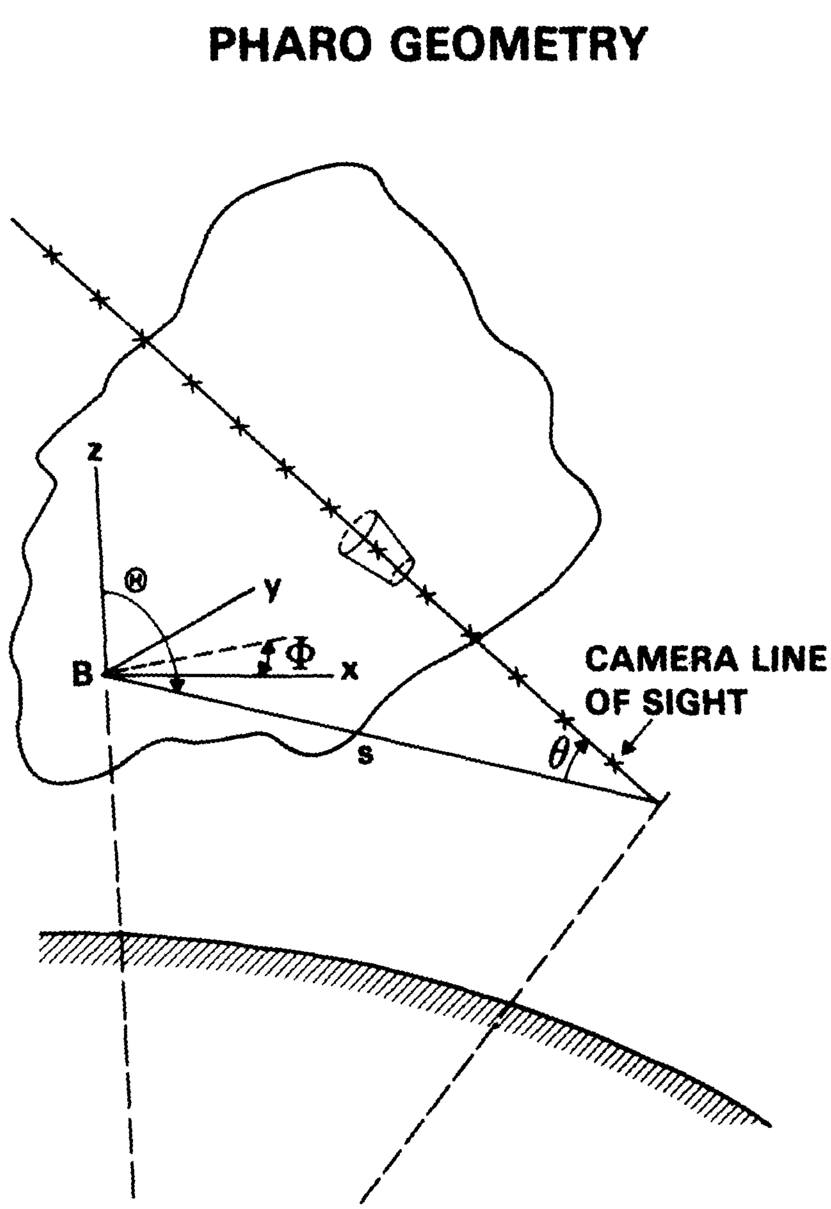


Fig. 3 — Line integration of volume emission from conical segments at a particular wavelength, along a ray, to obtain radiance. s is the distance between camera and burst point, B. Θ and Φ define the direction from burst to camera. θ and ϕ (not shown) define the direction of the camera line of sight relative to the burst point.

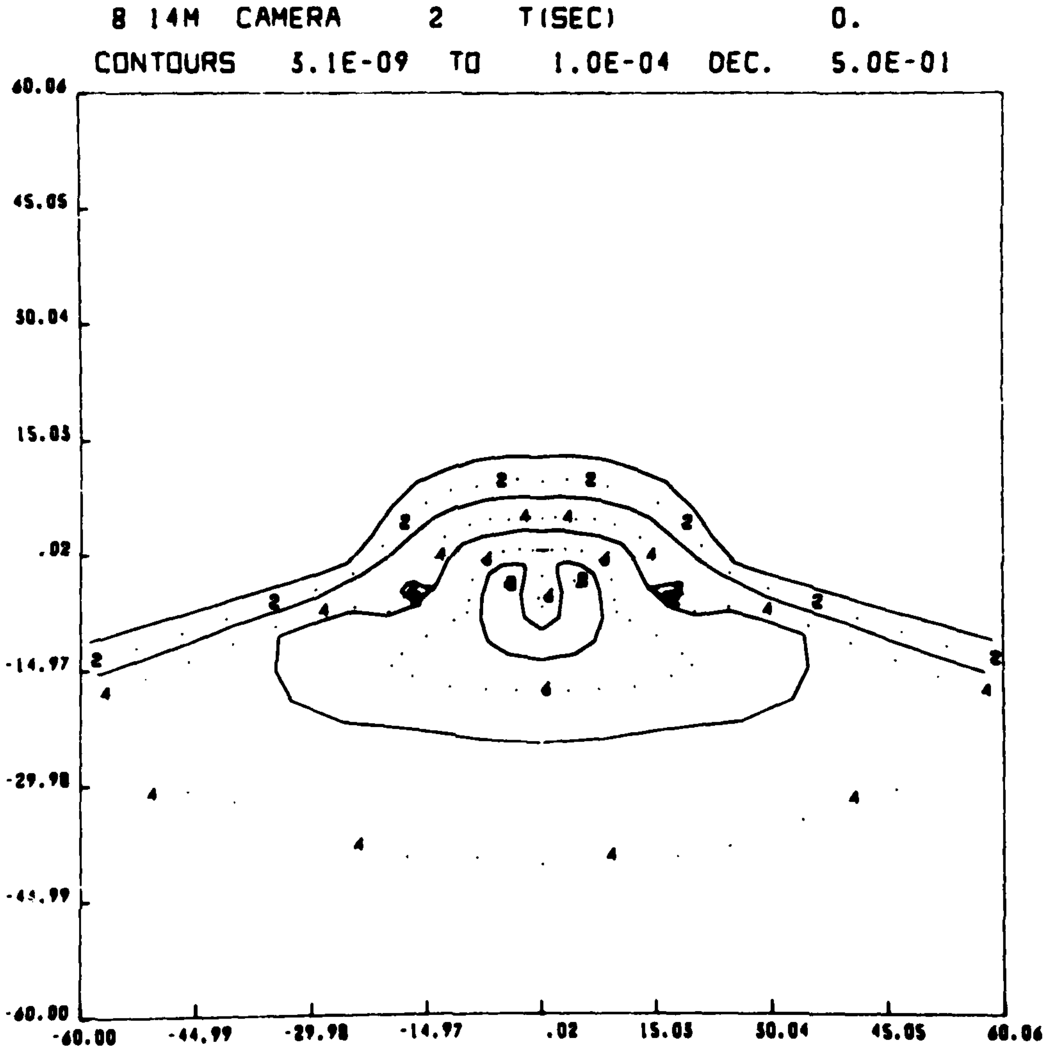


Fig. 4 — Radiance in the 8-14 μ band (watts/cm^{2}ster) from a high altitude burst ∿ 1. sec after burst. Abscissa and ordinate in degrees.

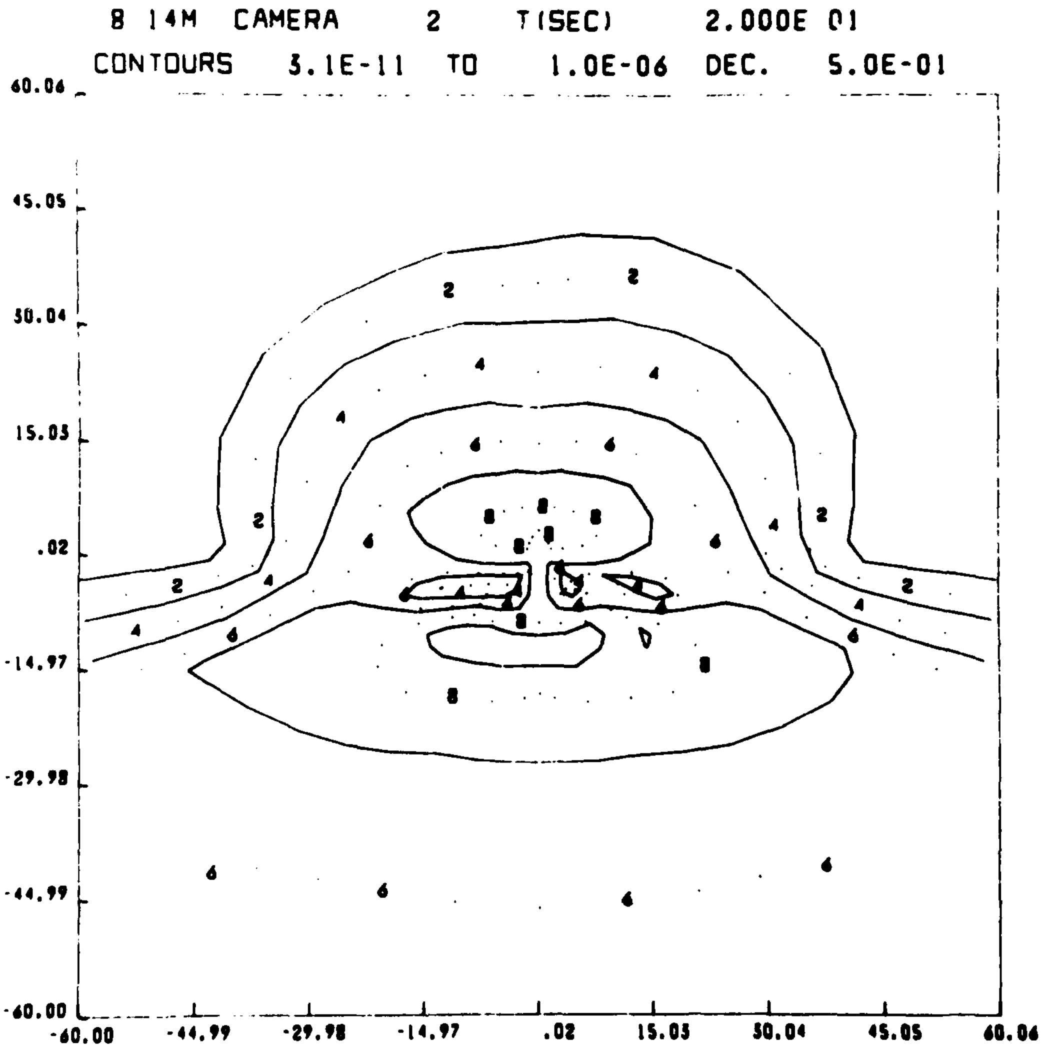


Fig. 5 — Radiance in the 8-14 μ band (watts/cm^{2}ster) from a high altitude burst ∼ 20. sec after burst. Abscissa and ordinate in degrees.

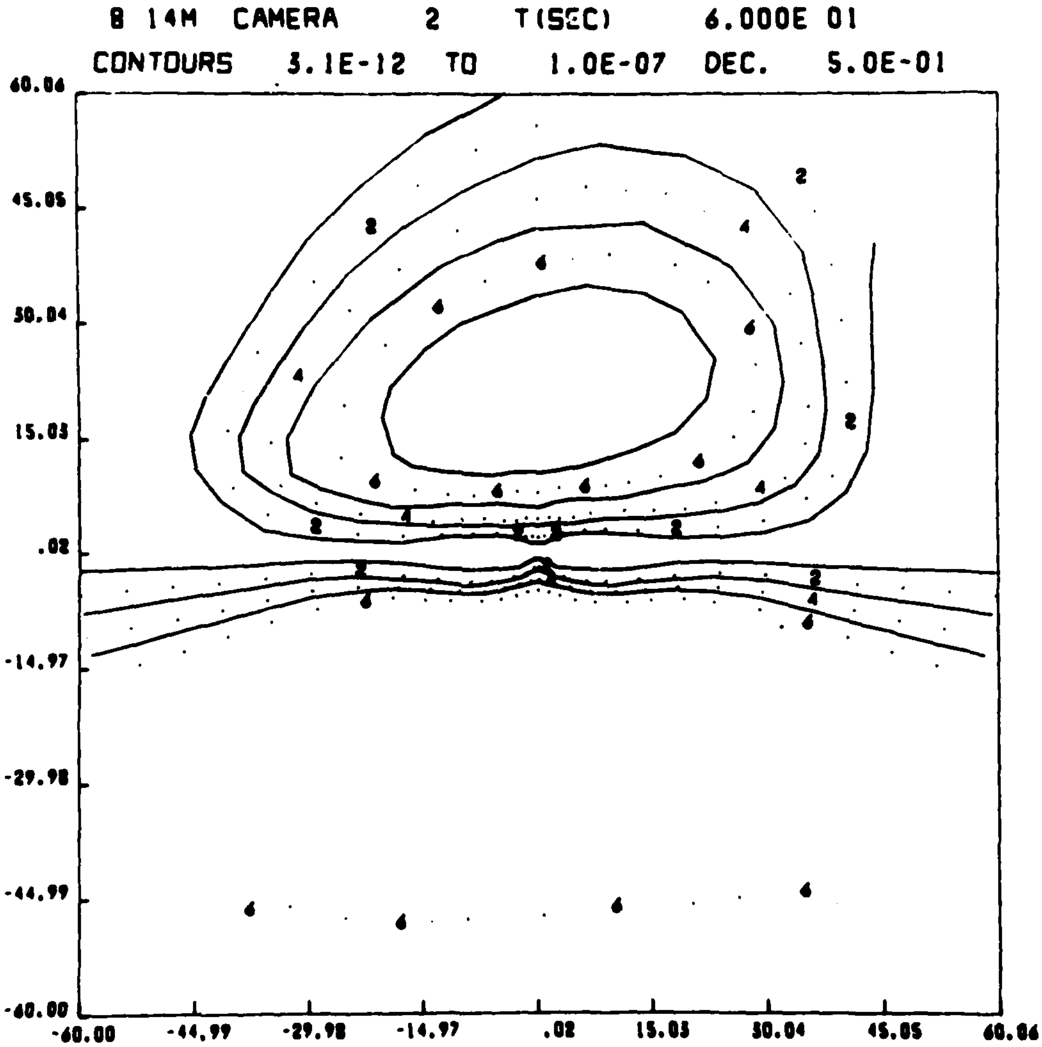


Fig. 6 — Radiance in the 8-14 μ band (watts/cm^{2}ster) from a high altitude burst ∿ 60. sec after burst. Abscissa and ordinate in degrees.

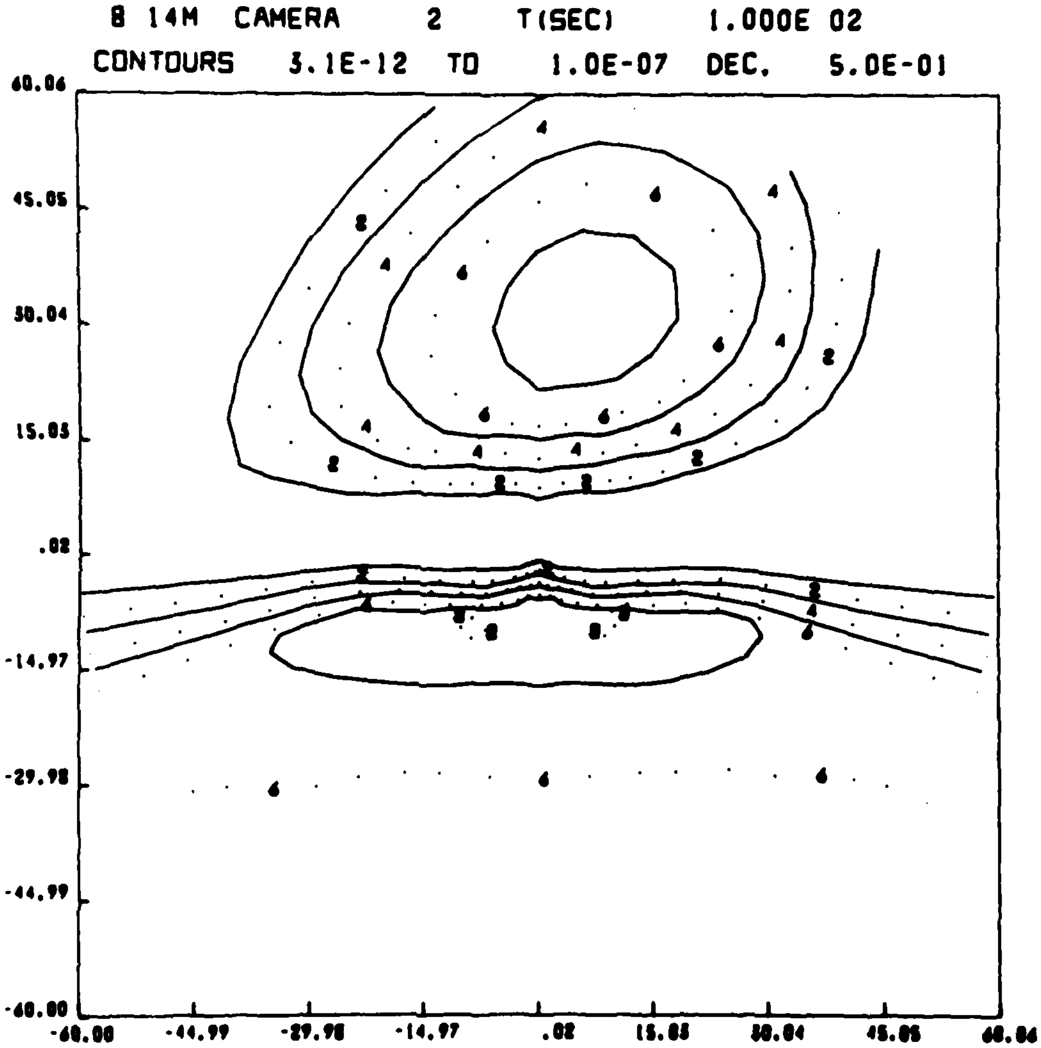


Fig. 7 — Radiance in the 8-14 μ band (watts/cm^{2}ster) from a high altitude burst ∼ 100. sec after burst. Abscissa and ordinate in degrees.

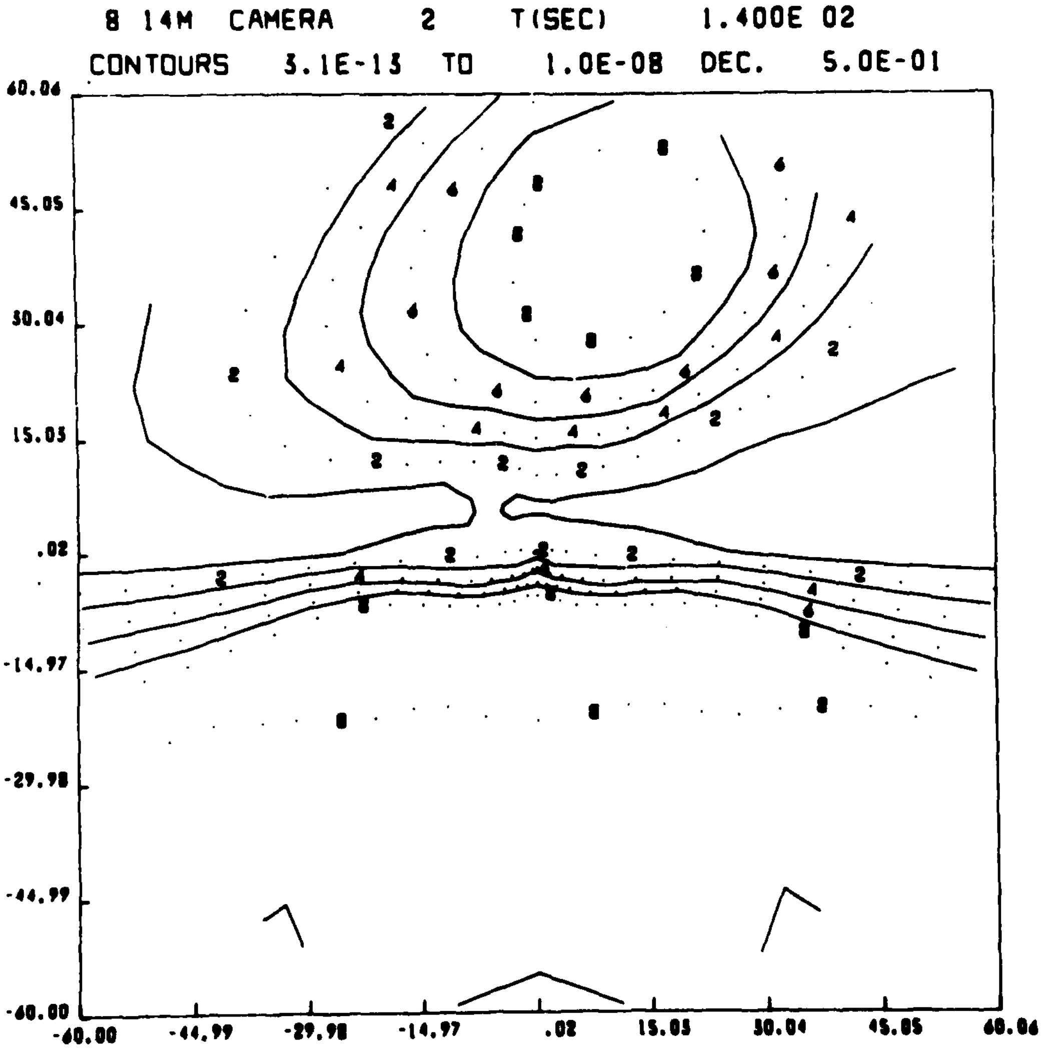
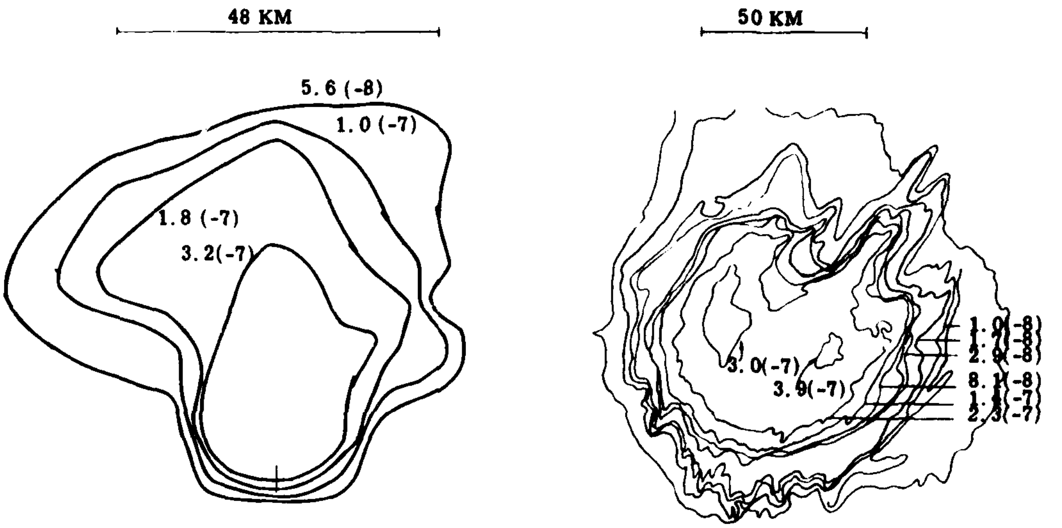


Fig. 8 — Radiance in the 8-14 μ band (watts/cm^{2}ster) from a high altitude burst $\sim$ 140. sec after burst. Abscissa and ordinate in degrees.



STATION KI
60 SECONDS
WATTS/CM^2 SR (3800 - 6800 Å)

STATION KI
57-58 SECONDS
WATTS/CM^{2}SR (3800 - 6500 Å)

Fig. 9 — PHARO radiance contour predictions compared with measured contours for a high altitude burst in the visible spectrum at ∿ 60. sec.

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