RADIATIVE RELAXATION RATES AND INTENSITIES DURING OUTER PLANET ENTRIES

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DR. LEIBOWITZ: This morning I would like to give you a review of the gas properties which can affect outer planetary entry probe radiative heat transfer.

The goal is to be able to predict the effect of processes such as radiative relaxation, radiative cooling, and equilibrium radiation intensities on entry. The purpose is to better quantify these processes in order to avoid overestimating the radiative transfer by an over simplified approach to the problem. By reducing these uncertainties in the knowledge of these processes, we hope to minimize the heatshield weight by reducing safety factors and performance limits that might otherwise have to be put in.

Figure 5-7 is a schematic diagram that roughly shows flow regions for an outer planetary entry probe. The atmosphere of the outer planets, as you know, is molecular hydrogen and helium, for the most part. Through the shock layer these gases are transformed into hydrogen atoms, ions and electrons. You can basically think of the shock layer in terms of three regions, neglecting the boundary layer. First we have a weakly radiating non-equilibrium layer. In this layer the shock heated gas undergoes chemical reactions and is transformed as it flows into the ionized species. Then we have the equilibrium layer where the gases are considered in local thermodynamic equilibrium and the radiation transfer can be calculated accordingly. Finally we have a high-temperature radiative cooling region where the hot gas radiates much of its energy away into the outer flow and by loosing that energy the temperature falls and it, therefore, radiates considerably less energy to the wall, thus causing lower heat transfer.

These three regions represent areas of separate topics of study. The non-equilibrium layer is the one that we have been emphasizing. In this region the radiation is proportional to the electron concentration. The electron concentration is initially

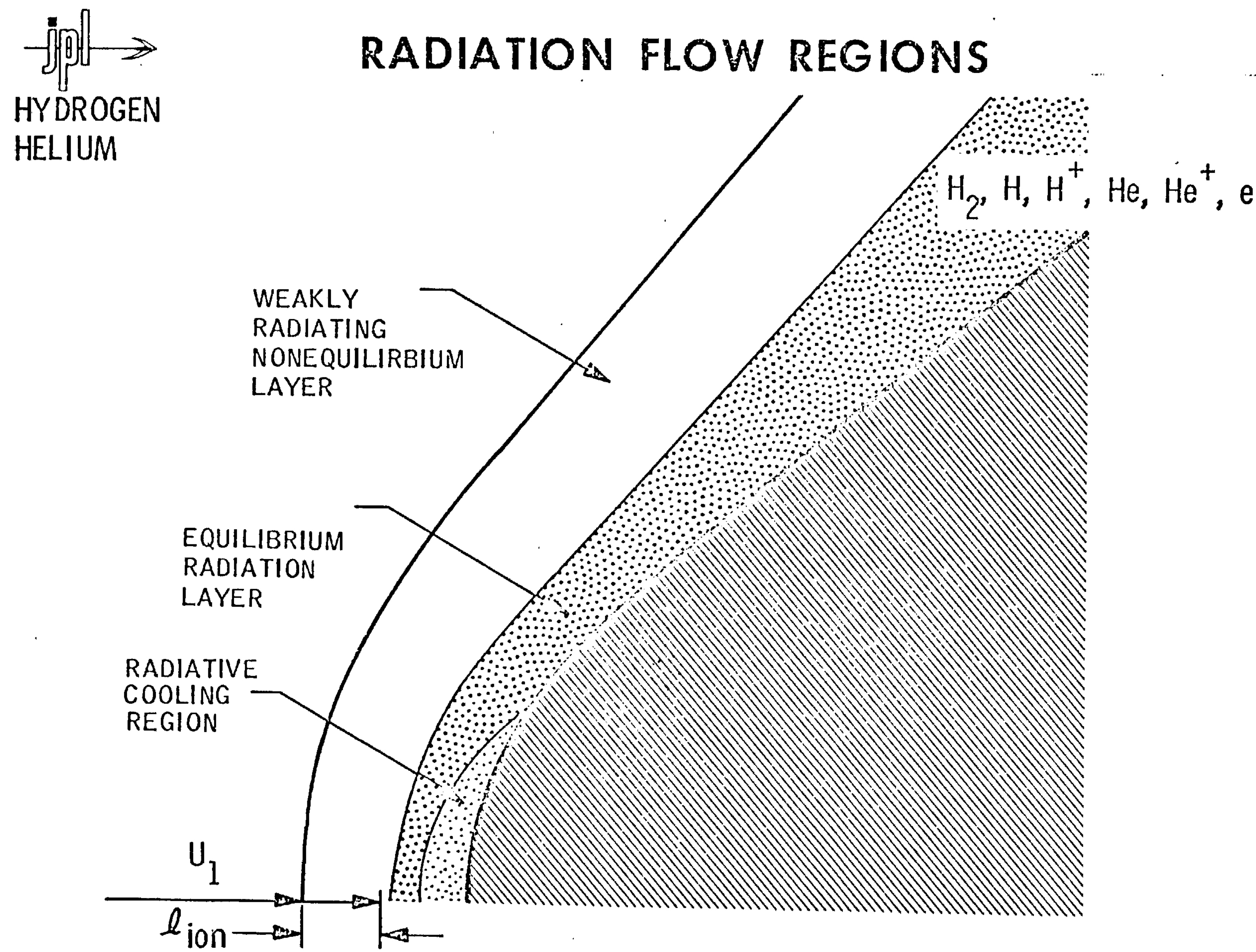
RADIATION FLOW REGIONS
HYDROGEN
HELIUM
H_2, H, H^+, He, He^+, e
WEAKLY RADIATING NONEQUILIRBIUM LAYER
EQUILIBRIUM RADIATION LAYER
RADIATIVE COOLING REGION
U_1
ℓ_{ion}

Figure 5-7

zero at the shock wave and then as the reactions take place it increases to an equilibrium value; therefore, when the electron concentration is much below the equilibrium concentration the radiation is much below the equilibrium radiation. So, in the case where the relaxation distance is long compared with the standoff distance you have a large region of virtually radiation free gas.

This is considerably different from the case of non-equilibrium radiation for Earth and Venus, where the non-equilibrium overshoot of molecular species behind the shock wave resulted in an increase in radiation over what the equilibrium theory would indicate.

Our approach has been to develop shock tubes which produce conditions as close as possible to entry, then to make measurements of the radiative and kinetic properties of the shock heated gases and finally, the experimental data is applied to flow field calculations in order to obtain entry heat flux. Data has been obtained both in a conical arc driver, shown in Figure 5-8 and a newly-developed annular arc driver, called ANAA shock tube. The ANAA shock tube deposits energy of a capacitor bank into a flowing gas which then immediately expands and cools before it can lose energy to the walls of the shock tube while it waits for a diaphragm to open. With this new shock tube, Jupiter and Saturn entry velocities and pressures, for the most part, can be simulated.

In the diagram of Figure 5-8, we see a capacitor bank which discharges a spark into a gas. The heated gas then rushes down the tube driving a shock wave ahead of it. The radiation emitted behind the shock wave, then, is measured by a series of spectrometers and monochromators. Hydrogen line and continuum channels are detected, including the profile of the H Beta line using a fiber optics slit system which can be used to get electron densities and temperatures directly.

EXPERIMENTAL APPARATUS

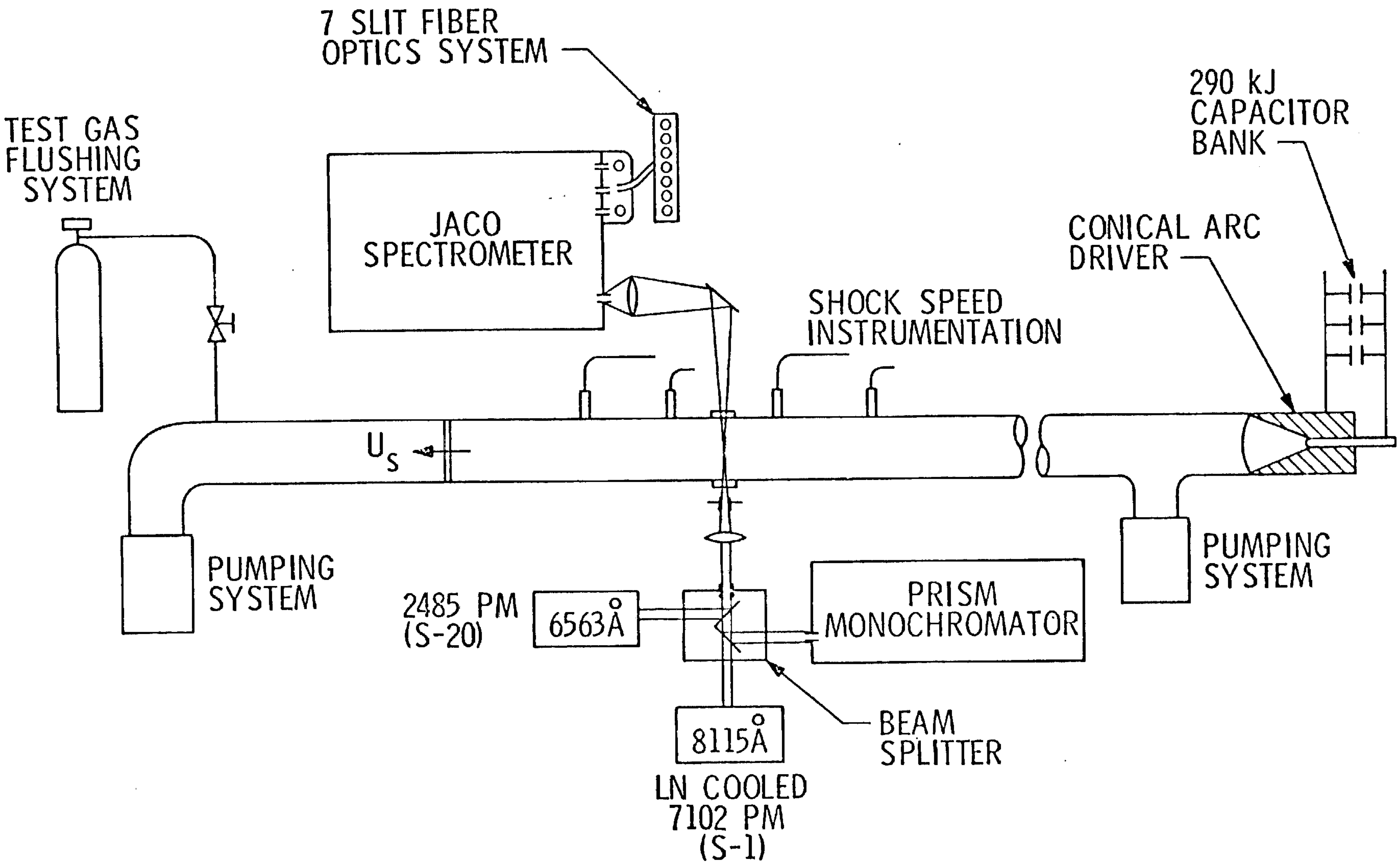

Figure 5-8

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 5-9 is our latest trace obtained last Friday and it is our closest attempt at simulating outer planetary entry conditions. This is for an initial pressure four torr and 26 kilometers per second. This roughly approximates peak heating for a Saturn entry. We have measured here the intensity of the H Beta line as a function of time. This is a magnified version. Intensity is down so, initially at the shock arrival, the intensity is virtually zero; then, as the chemical reactions take place and the electrons begin to be formed, the intensity suddenly jumps and then rapidly reach an equilibrium value. The relaxation distance is the distance between the shock arrival and when equilibrium is achieved. It is rather substantial: four centimeters compared with standoff distances. We will see that a little later.

Figure 5-10 is a plot of relaxation distance times the initial pressure in the shock tube as a function of the shock velocity. The dark points are the higher pressure data obtained with the ANAA shock tube. The solid line is a curve fit obtained from numerical integration of the ionization and dissociation reaction kinetics. By adjusting rate parameters one can see that there is rather good agreement on the dependence on the part of both the data and the calculations. The squares represent data obtained at a much lower pressure in the conical driver and while the data agrees very well at the higher shock velocities, it diverges somwhat at the lower velocities which seems to indicate the possibility of test time limitations in these low velocities.

With the kinetic data obtained by fitting the experimental results we can apply the kinetics program to the flow field case. This is the subject of the next talk by Dr. Kuo. It is with data such as this that we will be able to quantify the non-equilibrium effect for outer planet entry conditions.

SATURN ENTRY RADIATION RELAXATION

84.17% H_2 - 15.83% He
p_1 = 4.0 torr
U_1 = 26 Km/sec

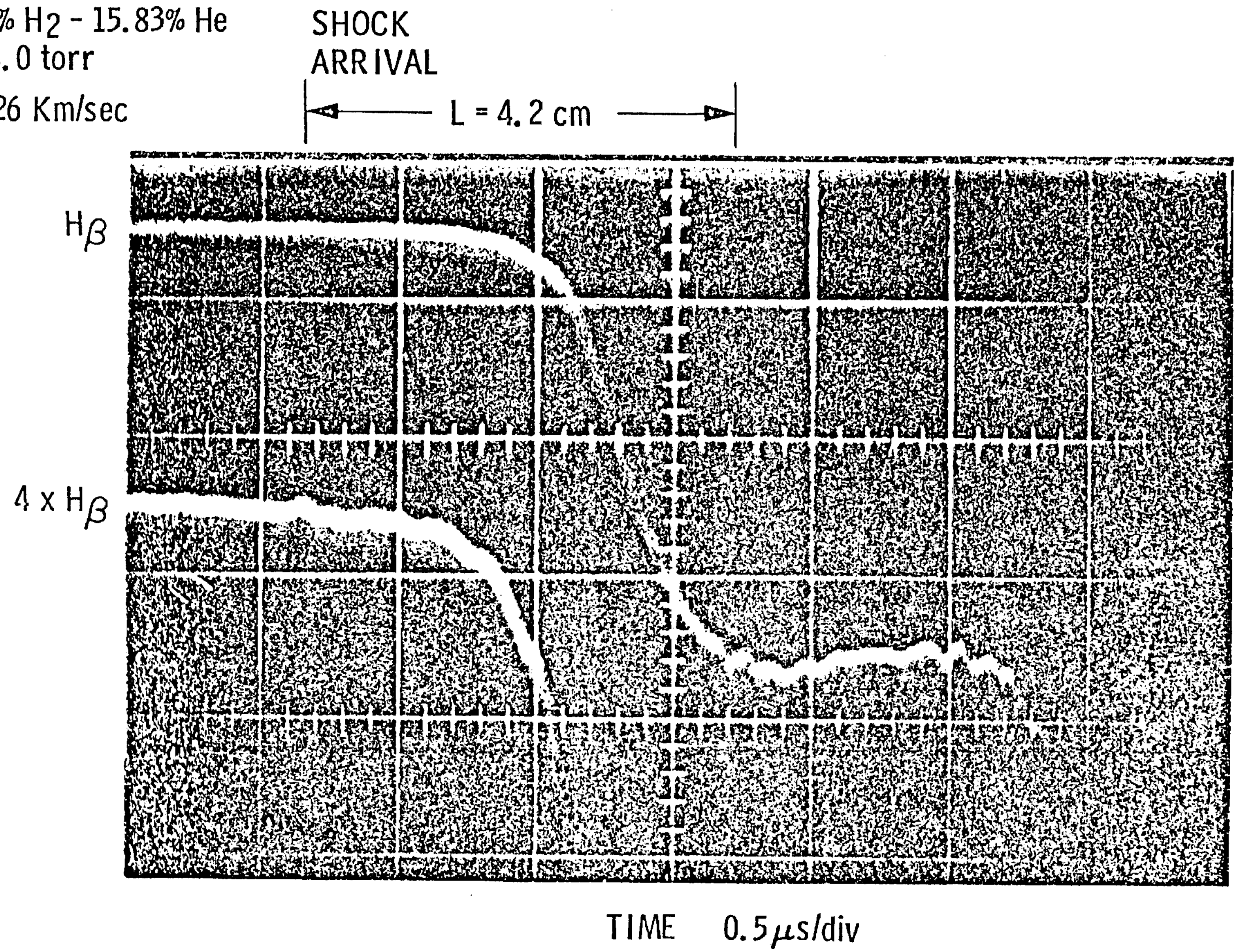

Figure 5-9

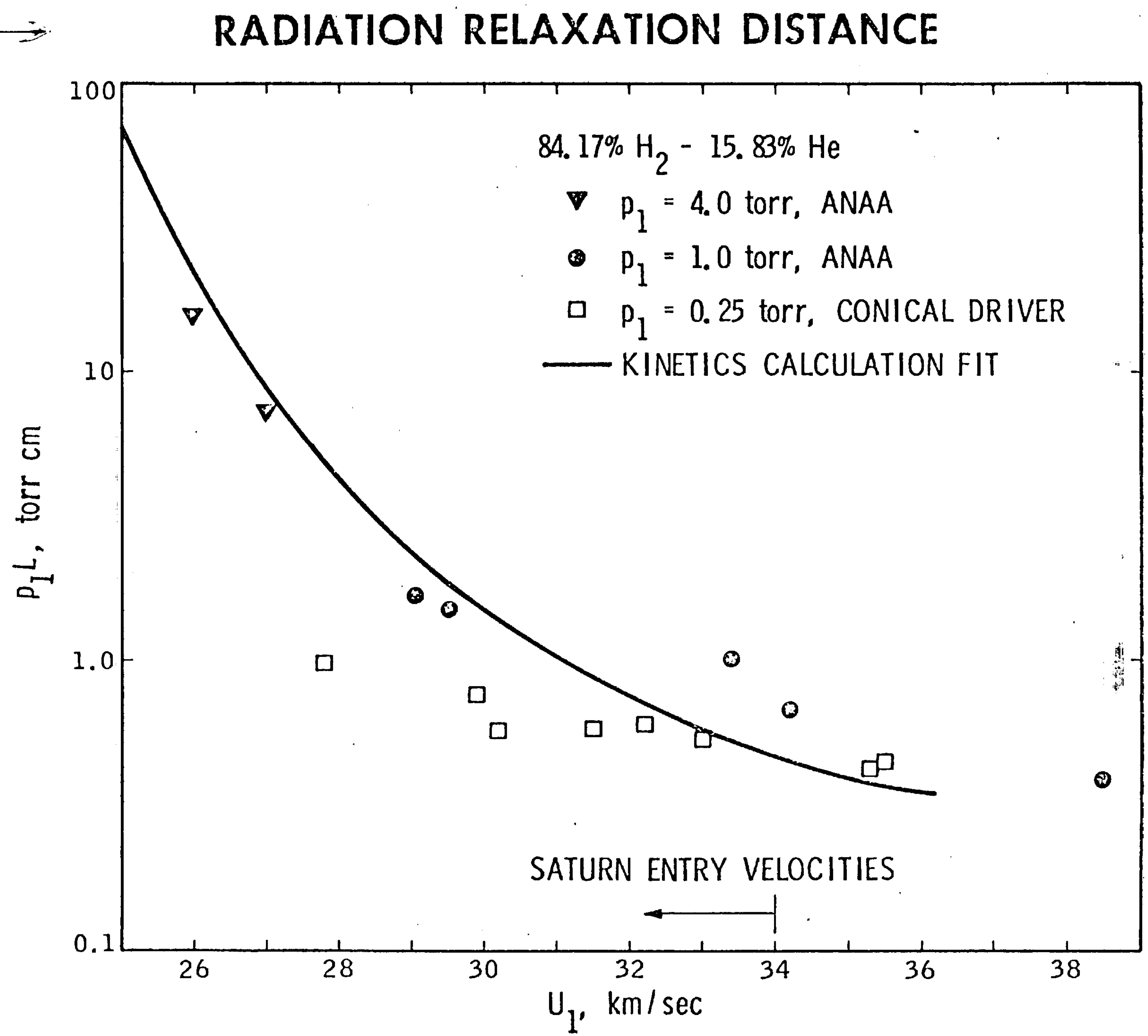
RADIATION RELAXATION DISTANCE
84.17% H2 - 15.83% He
p1 = 4.0 torr, ANAA
p1 = 1.0 torr, ANAA
p1 = 0.25 torr, CONICAL DRIVER
KINETICS CALCULATION FIT
SATURN ENTRY VELOCITIES
p1L, torr cm
100
10
1.0
0.1
26
28
30
32
34
36
38
U1, km/sec

Figure 5-10

We have made a rather comprehensive comparison of equilibrium hydrogen and helium radiation measurements with theory. We have covered ranges of temperatures from 10,000° to 20,000° Kelvin and electron densities that cover the full range of Saturn and Jupiter entry conditions. Figure 5-11 is a sample of some of the typical agreements that we have obtained. This is hydrogen line radiation and these are hydrogen continuum channels over a wide range of temperatures. As you can see, for the equilibrium calculations, we are very well able to predict what we measure in the shock tube. Throughout the full range of all conditions that we have covered we get a twenty-five percent agreement with the theory.

Concerning radiative cooling measurements, we've just begun to use the capabilities of the ANAA shock tube for this study. Radiative cooling could result in up to a seventy percent reduction in radiative heating during portions of Jupiter entry trajectory. Initial experimental data is in reasonable agreement with simplified calculations. This work is now being continued.

In conclusion, due to recently improved simulation facilities that are able to produce Jupiter and Saturn entry conditions, and the development of the non-equilibrium flow programs, we are in a good position now to accurately assess the effect of each of these radiative processes on the entry trajectories themselves and on the heatshield requirements.

UNIDENTIFIED SPEAKER: On that final chart, the curve you labeled as a function of lambda. It goes eight tenths, point three, and point sixty-five. Is that a peaking situation and, if so, what would cause that peaking?

MR. LEIBOWITZ: The top curve is line radiation which is considerably more intense than the continuum. The bottom two traces are continuum which increases with decreasing wavelengths.

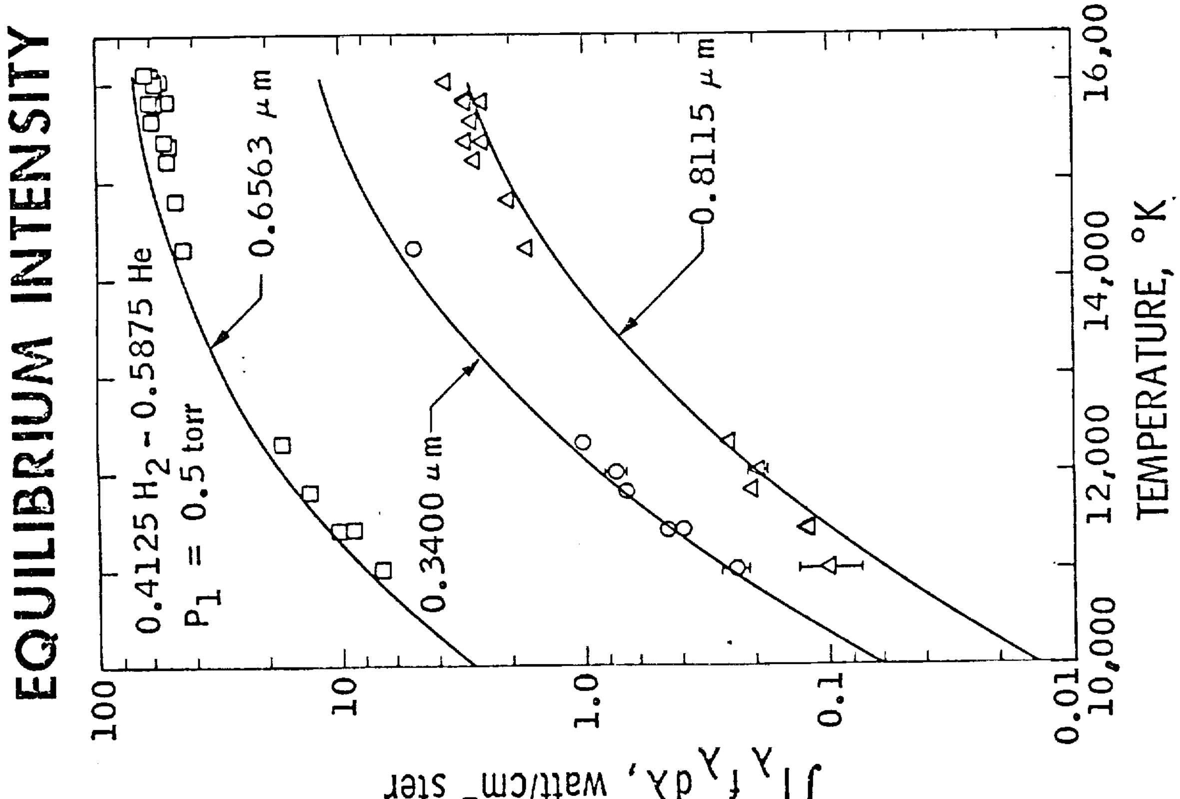
EQUILIBRIUM INTENSITY
0.4125 H_2 - 0.5875 He
P_1 = 0.5 torr
0.6563 μm
0.3400 μm
0.8115 μm
$\int I_\lambda f_\lambda d\lambda$, watt/cm^2 ster
100
10
1.0
0.1
0.01
10,000
12,000
14,000
16,000
TEMPERATURE, °K

Figure 5-11

UNIDENTIFIED SPEAKER: Lew, you said something about a seventy-percent reduction in radiative heating for Jupiter; would you expand on that a little bit: for what conditions?

MR. LEIBOWITZ: The question was under what conditions do you get a seventy-percent reduction in radiative heating due to the radiative cooling effect. That's a rough number. That would correspond, probably, to close to a worst case. I think that's a rather severe entry of, like, entry angles of greater than ten degrees. I don't have the exact numbers.

I don't claim that that would be an integrated value.

UNIDENTIFIED SPEAKER: I see; because the thing that strikes me is that Jupiter is such an energetic entry and the temperatures are so high and I think it would drive us towards equilibrium much better than the other planets.

MR. LEIBOWITZ: This is a different phenomenon when we talk about radiative cooling. That's not non-equilibrium. It's true that we expect the non-equilibrium effect to be much more significant, I think, at Saturn than for Jupiter.

UNIDENTIFIED SPEAKER: Could you make some kind of a comment about the sensitivity of this to the presence of those heavy elements we heard about yesterday.

MR. LEIBOWITZ: Yes. I haven't looked into that personally. Some work has been done here, I think, by Bill Page. His data that I have seen seems to indicate that it's not that sensitive. We haven't gone through this but our physical intuition seems to indicate that the heavy elements should be at the lower altitudes and one wonders whether it percolates up to the altitudes of severe entry.

UNIDENTIFIED SPEAKER: I thought Jupiter's peak heating was located at about the same height as the Pioneer 10 occultation data controversy.

MR. LEIBOWITZ: Yes?

UNIDENTIFIED SPEAKER: Howard, what is the pressure level at which peak heating occurs?

MR. LEIBOWITZ: All I know is about 10^7 dynes per square centimeter if that tells you anything. I think there is a two-fold problem. We can answer that question in a shock tube. The work has already been started at Ames on that. This can be continued. It is fairly easy to make shock tube measurements of what a little bit of one thing and another does. As I say, the initial indications are that it may not be that important. Hydrogen has always been an impurity that causes more problems in measurements of other compounds.

MR. SEIFF: Here is a comment. I have been working on this problem actively as I think everybody knows. There are two things that these gases can do. In the first place, I think their presence was a presumption. If they are present, they can do two things. One of them is they can absorb energy by dissociating - in trace constituents that will not be an important effect. The other thing that they can do is introduce line radiation in other locations than those that are being studied here. Again, with minor constituents, this should not be an important effect.

MR. LEIBOWITZ: I think all these species are present, probably, as ablation products, in much higher concentrations in the shock layer, than they would be in the atmosphere.

MR. OLSTAD: For the case of the Jupiter entry, a steep entry into a cold atmosphere which is the worst case in terms of heating rate, the shock layer is essentially optically thick. If you put any other radiators in there it doesn't matter unless it affects the temperature. The trace constituents won't affect the temperature too much. In that case, they shouldn't be too severe. It can have some effects on the non-equilibrium chemistry. As Lew mentioned, there have been some tests here at Ames which have introduced trace amounts of methane and ammonia. They have found, essentially, no effect on the amount of heating. But these were really trace amounts. I think there is some evidence that, in the Uranus atmosphere at least, they may be more than just trace amounts.

UNIDENTIFIED SPEAKER: At pressures of less than about a tenth of a dyne per square centimeter you are above the photochemical level and you will just have a hydrogen atmosphere, basically. There isn't even any methane to make photochemical products.

MR. SEIFF: Could we see that chart again that shows the relaxation lengths? (Figure 5-10)

I presume those were relaxation lengths - that would be the products of pressure and the relaxation lengths. That capital L there is the distance behind the shock wave? How was that defined? Is that when the radiation peaks?

MR. LEIBOWITZ: Yes. It is defined on the sample oscillograph. It's the distance to approach of equilibrium.

MR. SEIFF: For example: at one torr ambient pressure, at 32 kilometers per second, you might expect to get, say, one centimeter of relaxation distance?

MR. LEIBOWITZ: That's right. A flow-field case will be shown in the next talk for an entry velocity of 28 kilometers with a calculated length of four centimeters.