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SATELLITE DRAG STUDY

Grant Number NSG 8069

Final Report

For the period 1 April 1979 to 31 July 1980

Principal Investigator
Jack W. Slowey

Prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

October 1980

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The NASA Technical Officer for this grant is Dr. R.E. Smith, Code ES81, Space Science Laboratory, Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812.

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1. Introduction

The Smithsonian Astrophysical Observatory (SAO), under a grant from NASA (NSG8058), first began an analysis of the effects of atmospheric drag on the Skylab satellite, 1973-27A, in the fall of 1977. Under that grant we determined, from orbital data obtained from NORAD, the observed atmospheric drag on Skylab with a resolution of 5 days or better in an interval that was eventually to extend from March 1974 to the end of 1978. At the same time, we compared the observed drag with that predicted by an atmospheric model and made numerous forecasts, based on predicted solar and geomagnetic activity, of the orbital lifetime of the satellite.

The current grant work at SAO is essentially a continuation of the original grant work. Under this grant we continued to monitor the drag on Skylab and to make lifetime predictions up to the time of final decay. These activities were described in some detail in an earlier report and will not be covered again here. We also continued to act as consultant to MSFC in matters relating to our various atmospheric models and, in particular, to the implementation at MSFC of our most recent (1977) model. These activities have been conducted on a relatively informal basis, by telephone and letter, and will not be described here. We have also conducted a "post mortem" analysis to determine how the techniques that we used on Skylab might be improved in the future, especially with respect to the question of separating possible variations in area-mass ratio from departures of the atmospheric density from model values. A short summary of this work, together with some suggestions for future work, are given in what follows.

2. Technical Progress

We had hoped to utilize a second satellite in a comparative analysis of atmospheric drag during the final portion of the lifetime of Skylab. The object was to see if the drag on a second satellite could be successfully used to separate variations in the observed drag on Skylab that might be due to variations in the area-mass ratio from those that are due to variations in atmospheric density. An atmospheric model alone is not entirely adequate for this purpose since present models, as good as they are in representing the large variations in density that occur, are subject to appreciable systematic errors having characteristic times of up to a month or more. These errors are due mainly to failure of the decimetric solar flux to adequately represent the variations in the solar EUV radiation that actually heats the thermosphere and to similar inadequacy of the planetary geomagnetic index as an indicator of the heating associated with geomagnetic disturbance (and of present models of that very complex phenomenon). Except for short intervals in which

geomagnetic disturbance may dominate, the densities determined from drag on different satellites are generally quite consistent among themselves. Thus it should be possible to infer density at another location with greater accuracy from the drag on a satellite of known area-mass ratio than is possible from any model based on the usual geophysical parameters. Of course, a model would still be required to provide a means for interpolating between the location of the probe satellite and the desired location.

Unfortunately, the problems of data acquisition, program development (mainly the conversion of several large programs to run on a new computer), and processing proved to be too great to carry out the projected analysis within the constraints of this grant. Instead, we made use of densities we had previously obtained from the drag on the Explorer 32 satellite (1966-44A) to make a comparison with the orbital accelerations of Skylab that we had determined under the earlier grant (NSG 8058). The interval covered by this comparison was 265 days beginning in late March, 1974.

The orbital acceleration (rates of change of the mean motion) of Skylab that we determined from the available NORAD orbits are plotted for this interval in Figure 1. These were obtained by drawing a smooth curve through the observed values of the argument of latitude $(M + \omega)$ and numerically differentiating the curve using a 5-day time-step. In the same figure are shown the corresponding accelerations determined by differentiation of the results of numerical integration of the orbit using an atmospheric model and, at the bottom, the ratios of the observed accelerations to those computed from the orbit integration. The model used in the integration was an updated version of Jacchia's 1970 model (Jacchia, 1970) and the assumed area-mass ratio was 0.0369 cm^2/g. The drag coefficient was allowed to vary around the orbit, but the effective value was very close to 2.24 throughout the interval.

The relatively large short-term variations in the orbital acceleration seen in Figure 1 are due to variations in thermospheric heating by both solar EUV radiation and the particle precipitation and/or ionospheric currents associated with geomagnetic disturbance. In models, these two heat sources are tied, in the first instance, to the 10.7-cm solar radio flux and, in the second instance, to the K_p planetary geomagnetic index. In Figure 2, we have plotted 5-day means of both the 10.7-cm flux and the K_p geomagnetic index, on scales that are roughly equal in terms of their expected effect on the exospheric temperature of the atmosphere (the scale for K_p is slightly exaggerated in this regard compared to that for $F_{10.7}$). As can be seen, the two indices are quite independent of each other and may act either in unison or in opposition.

In Figure 4, we have plotted the exospheric temperature T_∞' that results from the 1970 model when only the short-term variation in the 10.7-cm flux (the so-called "27 day" variation) and the geomagnetic variation are taken into account. These temperatures were computed from

$$T_\infty' = 665.2+1.8\ (\ F_{10.7} - 85.)\ +28\ K_p + 0.03\ \exp\ (Kp),$$

where $F_{10.7}$ and K_p are the 5-day mean values from Figure 2. We give them here only to better illustrate the expected short-term variations in density in the interval being studied. Note that these temperatures differ somewhat in detail from the computed accelerations in Figure 1. This is because the values in Figure 1, as a result of the differentiation process, actually represent means over a slightly longer interval than 5 days.

In comparing the observed acceleration of Skylab from Figure 1 with either the corresponding model values or the temperatures of Figure 3, it will be noticed that several of the expected sharp maxima or minima are missing in the observed values. It is these points on the plot that result in the more prominent "outlyers" in the ratio of observed to computed acceleration. There is little doubt that some of these apparent departures from the model are, in fact, due mostly to errors in the observed values resulting from the relatively crude method used to derive them. And, it follows that the scatter in the values of the ratio is adversely effected generally for the same reason. This difficulty could, of course, be overcome by differentiating with a considerably larger time step, but this would automatically rule out the possibility of resolving shorter-term variations of any kind.

In Figure 4 we have plotted 5-day means of atmospheric densities obtained from analysis of the drag on the Explorer 32 satellite. The densities are those at the effective height (approximately 1/2 scale-height above the true height) of perigee. The average effective height in the interval plotted was about 300 km. These densities were obtained by direct analysis of radar observations from selected sensors. The densities were originally determined with a general resolution of 1 day and a resolution of 0.5 day during larger geomagnetic disturbances. The 5-day means plotted in the figure should have a relative precision of close to 1%.

These densities confirm the accuracy of the model with respect to 4 of the 5 worst values of the ratio in Figure 1. The exception is the point at MJD 42205, where the minimum predicted by the model and missing in the Skylab accelerations is also missing in the densities determined from Explorer 32. Other differences in the Skylab accelerations are also confirmed as being atmospheric in origin and not due to errors in the observed values.

At this point we should mention that our older atmospheric models are not currently operational at SAO due primarily to a change in computers. It was our intention in the present analysis to compute model values for both Skylab and Explorer 32 using our most recent atmospheric model (Jacchia, 1977), which is operational, and to make a comparison between the two satellites using the ratios to these values. Much to our surprise, however, the orbital accelerations of Skylab computed with the new model did not agree in detail with the observed values as well as did those from the older model nor did the densities computed for Explorer 32 represent the details of the observed values as well as it was expected they would.

It is not yet known whether this apparent difficulty with the new model is intrinsic or is somehow due to the way it was implemented in the particular circumstances. The only other application of the model that we have made in a drag situation was during the final decay of Skylab. It seemed to perform quite well in that case. That was hardly a definitive test, however, and it may well be that the most important result of the present analysis is that it revealed a major difficulty in the model-related, apparently, to the "improved" model of the geomagnetic variation that it incorporates.

When means of the computed densities for Explorer 32 were taken over 10-day intervals, they were quite smooth and did reproduce most of the systematic departures observed in the ratios for Skylab. In view of the difficulties with the model, we do not feel that we are justified in presenting those results as proven fact, however. We must, at least for the time being, consider the analysis to have been "inconclusive".

3. Conclusions and Recommendations

Our experience with Skylab demonstrated the need for an automated procedure for the high-resolution determination of densities from satellite drag. For reasons of efficiency, this should be an analytic procedure and, like the program that previously existed at SAO, should be based on direct analysis of the individual observations of the particular satellite in order to yield the greatest possible precision and time resolution. As a practical matter, it should be fully automatic and free of reliance on hand methods of any kind. It would be extremely valuable in a variety of programs in orbital dynamics, such as the studies we made of the drag on Skylab and the kind of comparative analysis we suggest is feasible in the case of satellites with unknown or varying area-mass ratios, and as a research tool that could contribute significantly to the improvement of models of the thermosphere and exosphere. We recommend that MSFC seriously consider the development of such a program.

We would also recommend that consideration be given to the possibility of utilizing this program in a project to monitor a small number of satellites on a continuous basis. No densities from satellite drag have been determined in any appreciable quantity since 1974. There are, however, some problems in thermospheric structure and model development that would benefit greatly from the availability of such densities. There is strong evidence in measurements of solar EUV irradiance, for example, of major differences between the current solar cycle and the previous one (Hinteregger, 1979). Our analysis of Skylab revealed that the response of the atmosphere relative to the decimetric flux was not greatly different in the two cycles. The exact nature of what difference may exist remains to be seen, however, and it would seem that drag analysis offers the only means by which it can be accurately determined. Densities determined from drag have the advantage of continuity (the drag record extends back to 1958) and freedom from the problems of cross-calibration between experiments that is lacking in densities determined by mass-spectrometers and other satellite-borne instruments.

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Jacchia, L.G.

1970 New static models of the thermosphere and exosphere with empirical temperature profiles. Smithsonian Astrophys. Obs. Spec. Rpt. No. 313, 87 pp.

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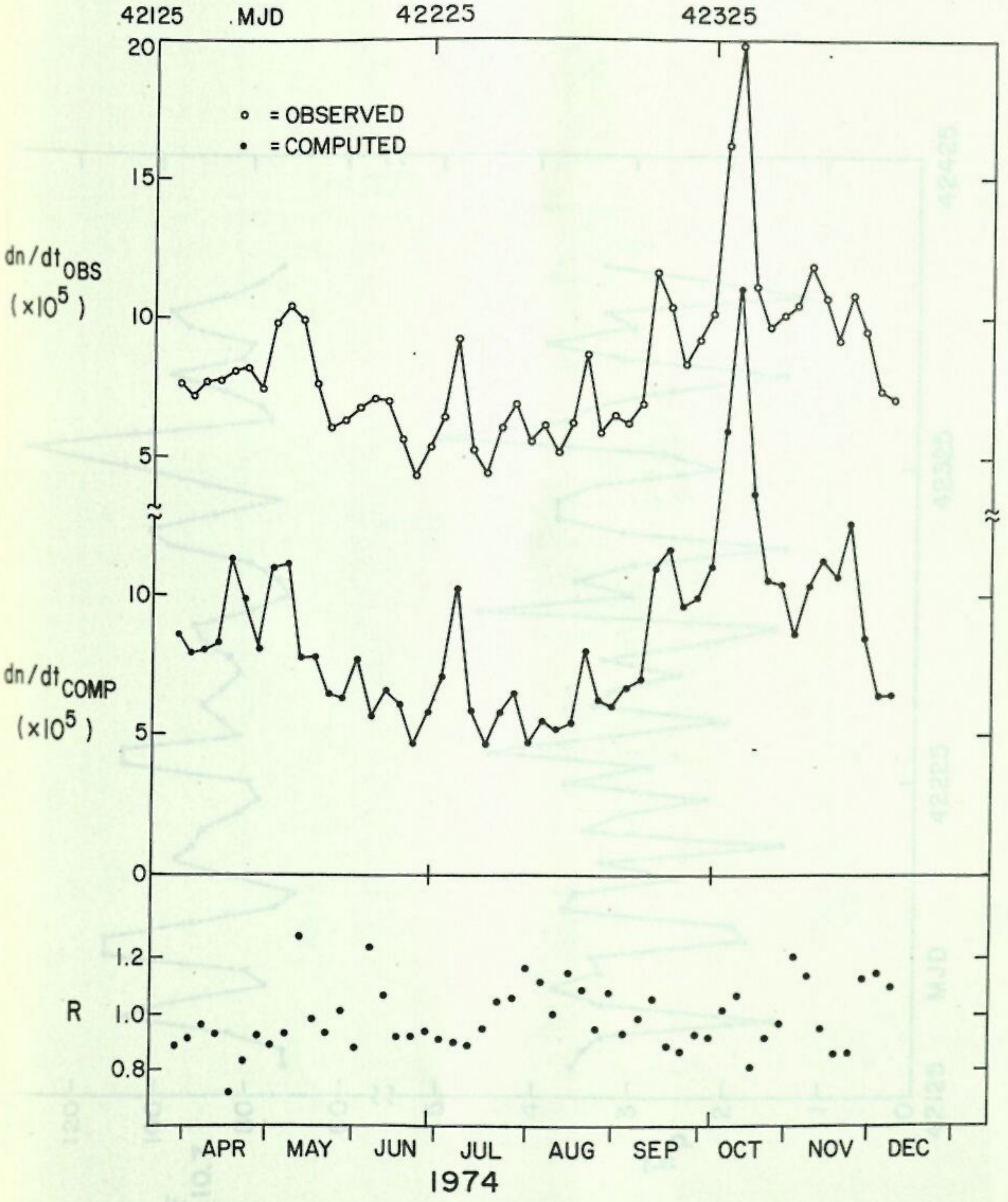
These captions pertain to the following figures (1-4).

Figure 1. Observed orbital acceleration of Skylab (top), acceleration computed from an atmospheric model (middle), and ratio of observed to computed acceleration (bottom).

Figure 2. 5-day means of 10.7 cm solar flux (top) and K_p geomagnetic index (bottom).

Figure 3. Exospheric temperature computed for just the 27-day variation and the geomagnetic variation.

Figure 4. 5-day means of observed densities at effective height for the Explorer 32 satellite.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MJD
42225
42325
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● = COMPUTED
dn/dt$_{OBS}$ (×10^5)
dn/dt$_{COMP}$ (×10^5)
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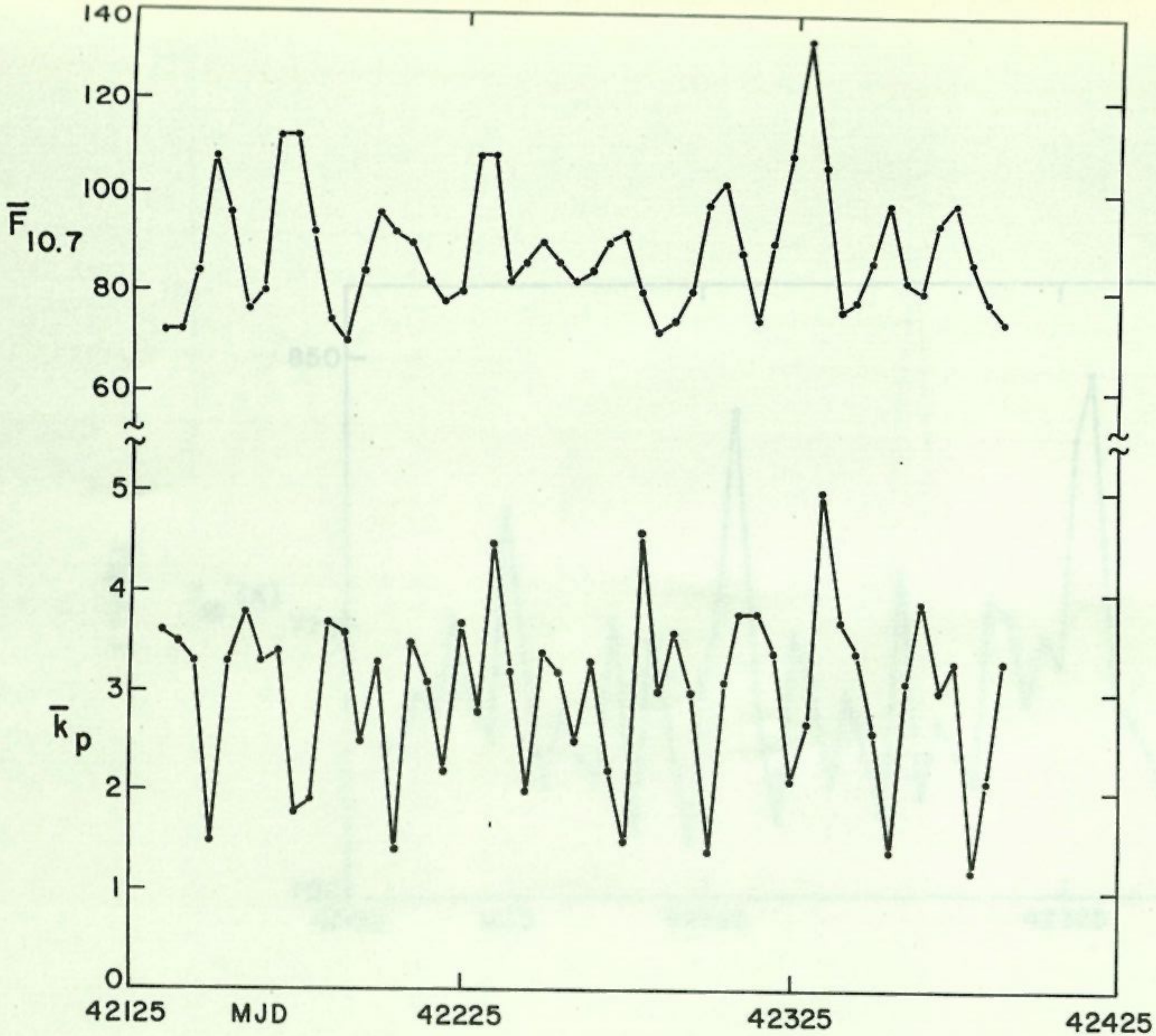
15
10
5
10
5
0
1.2
R
1.0
0.8
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1974

Figure 1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120
100
80
60
5
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3
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$\overline{F}_{10.7}$
$\overline{k}_p$
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MJD
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42325
42425

Figure 2

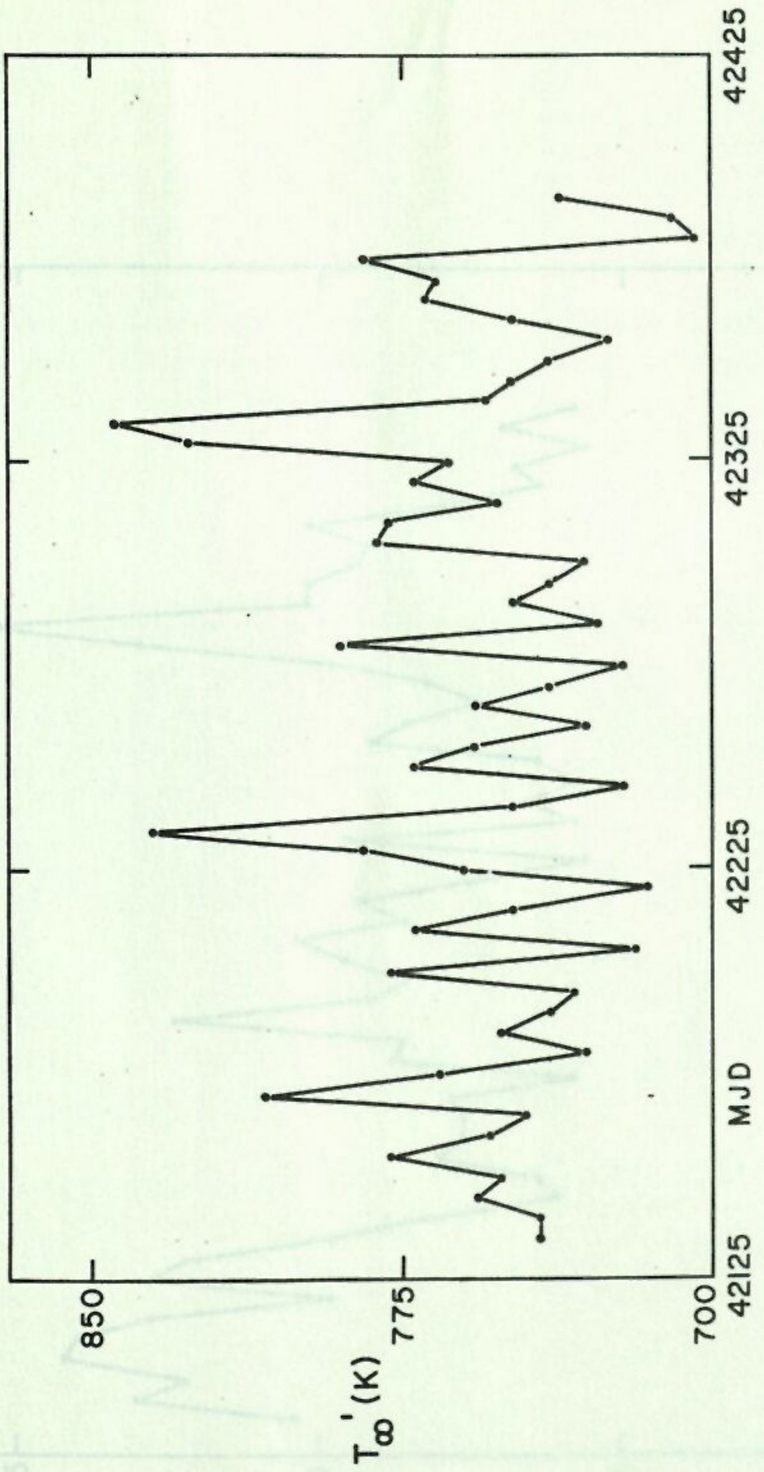

Figure 3

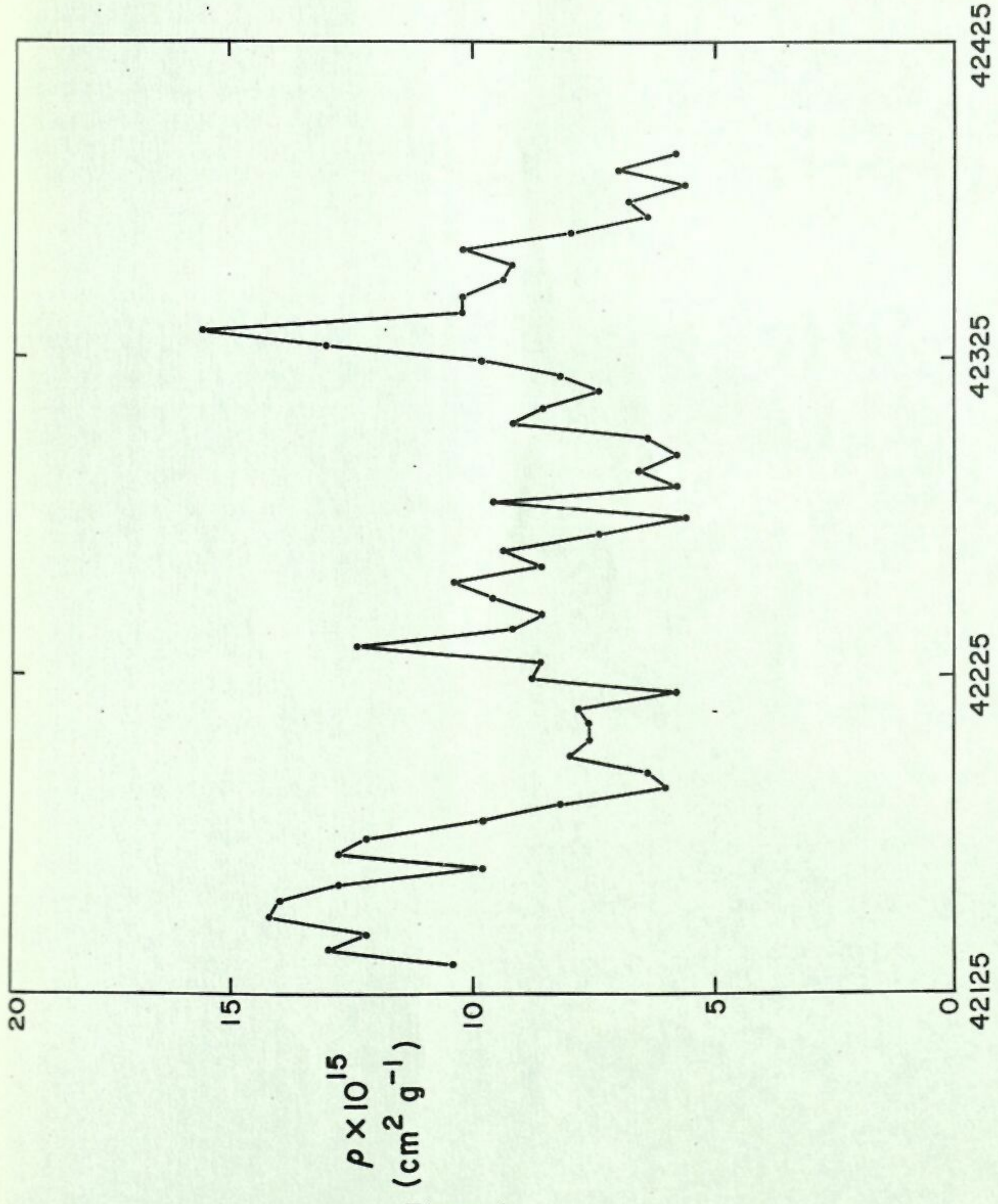

Figure 4