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A PARAMETRIC STUDY OF INTERSTELLAR HELIUM ATOMS INCIDENT UPON T--ETC(U)
JAN 81 R R MEIER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Calculations of the intensity of interstellar helium atoms at earth orbit are made with a model which takes into account perturbation of the Maxwell-Boltzmann velocity distribution by solar gravity and photoionization loss. Seasonal sky maps are presented and assessments of the sensitivity of the intensity of atoms in the vicinity of the earth to the various parameters of the gas are given.

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CONTENTS

A PARAMETRIC STUDY OF INTERSTELLAR HELIUM ATOMS

INCIDENT UPON THE EARTH

# I. INTRODUCTION

Due to the relative motion of the solar system and the interstellar medium, neutral interstellar atoms can penetrate deep within the interplanetary regime. Studies of the backscatter of solar H Lyman α and He 584A radiation have demonstrated that it is possible to deduce information about the density, temperature, and velocity of such atoms from studies of the sky background radiation (see reviews by Holzer, 1977 and Thomas, 1978). However, additional observations to improve our knowledge of the local interstellar medium parameters are desirable to reduce uncertainties evident in the ranges of values determined by such methods.

One way to do this is to directly measure the intensity or flux per unit solid angle of interstellar atoms in the vicinity of the earth's orbit. Several groups are actively pursuing such programs with various experimental techniques. The purpose of this report is to provide theoretical models of atoms impacting the earth in an attempt to predict detailed characteristics of the atomic intensity pattern at 1 a.u. Atomic intensities are provided only for helium, as hydrogen is lost via charge exchange with the solar wind (and photoionization to a lesser extent) inside 2-6 a.u. from the sun.

Plots of the seasonal variation of the intensity and mean velocity are presented and the dependences upon the parameters of the

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interstellar gas and its interaction with the solar system are delineated. Recommendations are provided for the best times of year to obtain measurements of specific parameters.

## II. THE MODEL

The intensity of atoms can be written as

$$I \text{ (atoms cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}) = \int_{v_m}^{\infty} |\underline{v} - \underline{v}_E| \, f(v) v^2 dv$$

where $\underline{v}_E$ is the earth velocity vector in inertial coordinates (right ascension and declination), $|\underline{v} - \underline{v}_E|$ is the atomic velocity as seen in a coordinate system moving with the earth, $v_m$ is the minimum allowable velocity (for an atom with zero velocity at infinity), and f(v) is the velocity distribution, as perturbed by solar gravity, radiation pressure, and loss processes. The integration is carried out over the atomic velocity v in spherical velocity coordinates. Details of the model are given by Meier (1977) and are not repeated here.

The procedure for computing I first requires selection of the observation direction in order to determine the relative velocity, $\underline{v} - \underline{v}_E$. In stepping through the integration, knowledge of the observation direction and also the magnitude of the independent variable v permits computation of the relative velocity $|\underline{v} - \underline{v}_E|$ and the direction of $\underline{v}$, and finally the phase space distribution function f is evaluated. Gaussian quadratures are used for integration with as many as 32 ordinates for varying sub-intervals of v, depending upon the smoothness of the function. Limiting analytic solutions were evaluated (similar to those described by Meier, 1977) for comparison with results from the computer code.

In all cases the agreement was excellent. The present procedure represents a significant improvement over the approximate numerical technique used previously (Meier, 1977) for computing atomic intensities; the results presented herein are thus considerably more accurate.

## III. INTENSITY PATTERNS

Figure 1 is a qualitative sketch showing typical trajectories of interstellar atoms moving through the solar system. Figure 2 shows a "standard" set of sky maps of the atomic helium intensity in right ascension and declination. The actual values of right ascension indicated on the upper horizontal axis of the plots apply to the character spaces below the zero of the "units" column of each number. Intensities are given for every 4° in $\alpha$ and 4° in $\delta$. In each graph, the alpha-numeric character set is normalized to the maximum value of the intensity on that day ($I_{max}$). The numerical value of the maximum is given at the bottom of the intensity plot and is indicated as an "E" character in the table just below. In the contour graph itself, the "E" has been replaced by an "+" for easy visual location. Each successive intensity grouping is lower than the next by 1/3. Thus, on day 1 (Figure 2a), the character "D" represents all intensities between $1.88 \times 10^5$ and $2.51 \times 10^5$ atoms $cm^{-2}\ s^{-1}\ sr^{-1}$.

The mean velocity at each point is arbitrarily defined as

$$\bar{v} = \frac{\int |\underline{v} - \underline{v}_E| \left(\frac{dI}{dv}\right) dv}{I}$$

and is listed for $I_{max}$ just below the intensity plots. The total flux incident upon the earth, $\int I d\Omega$ is also given on the same line.

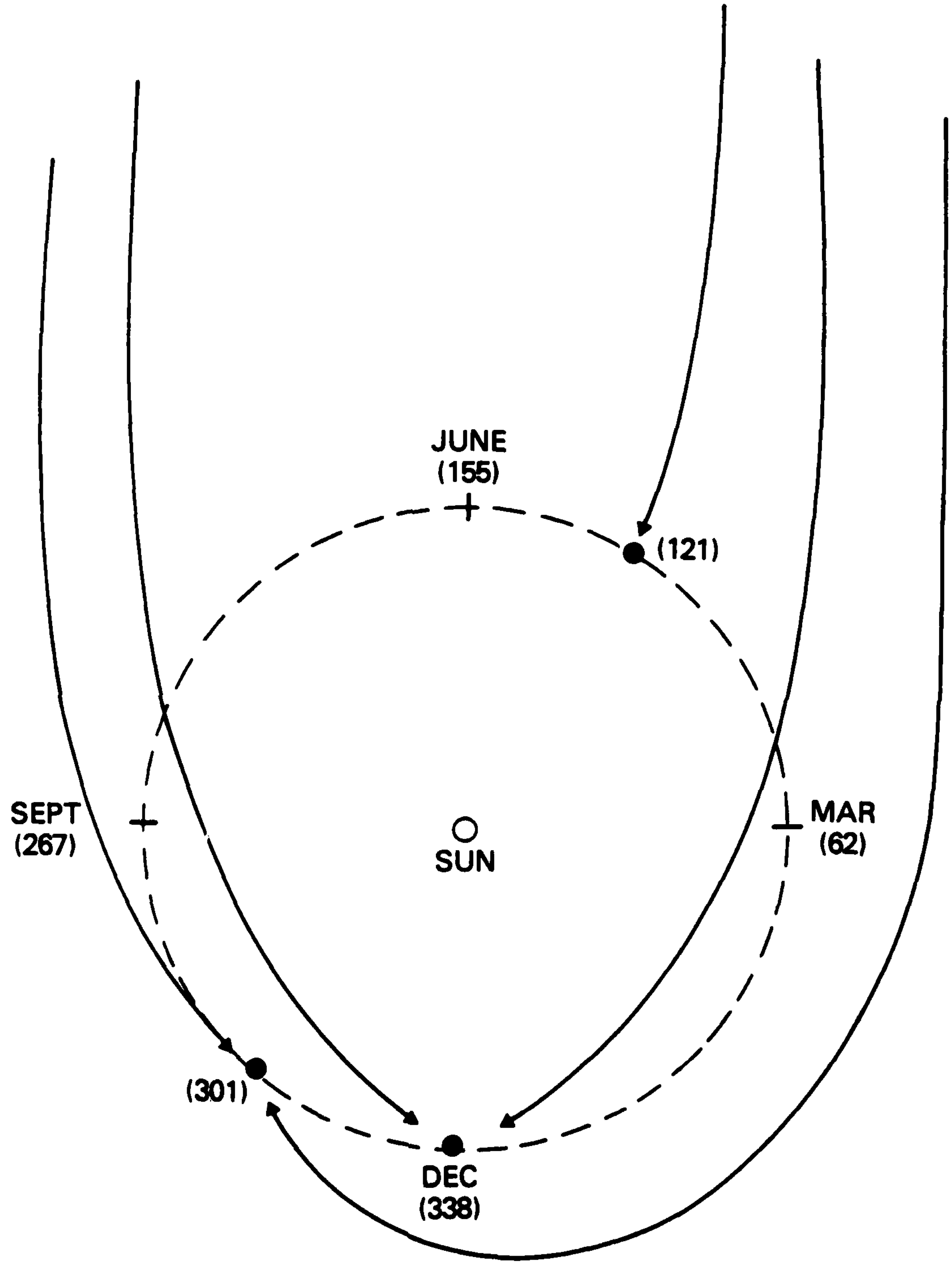
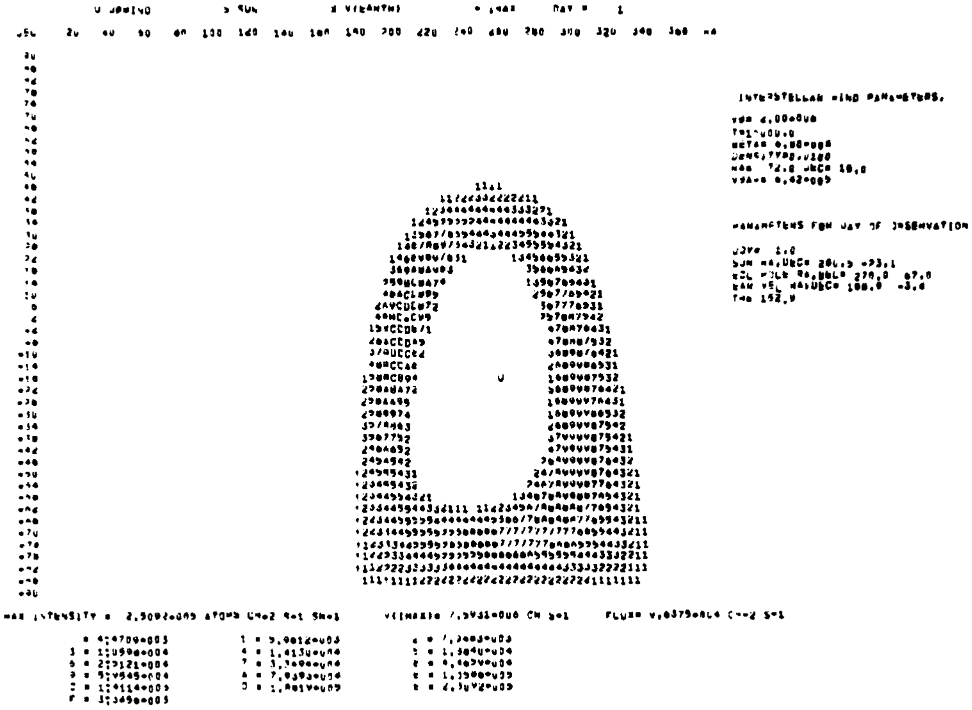



Fig. 1 — Sketch of orbits of interstellar helium atoms passing through solar system, projected into the ecliptic plane. The numbers in parentheses indicate the day-of-year for various positions of the earth and months when the earth is at closest approach to upwind, downwind, and 90° conditions.



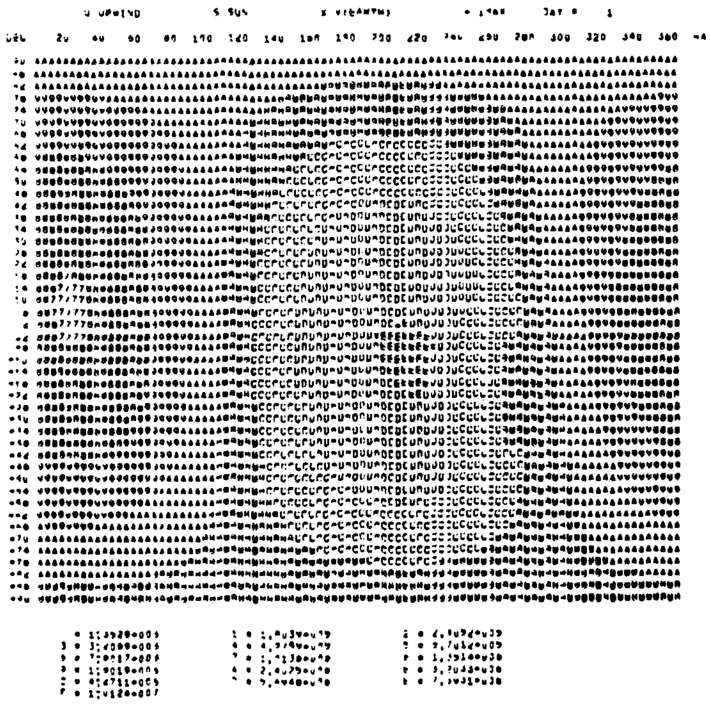
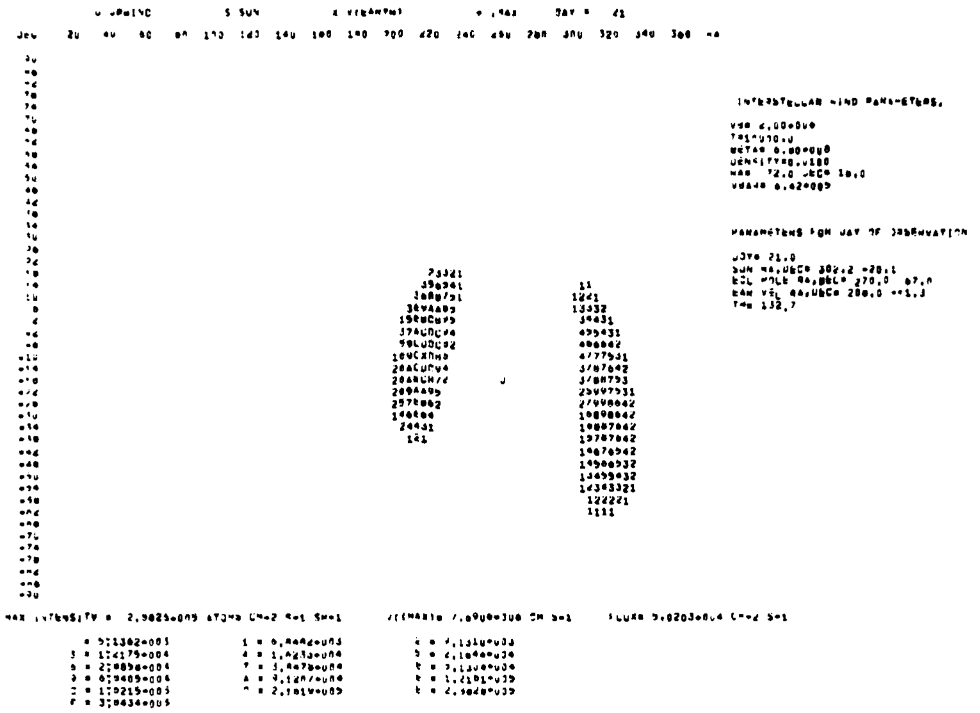
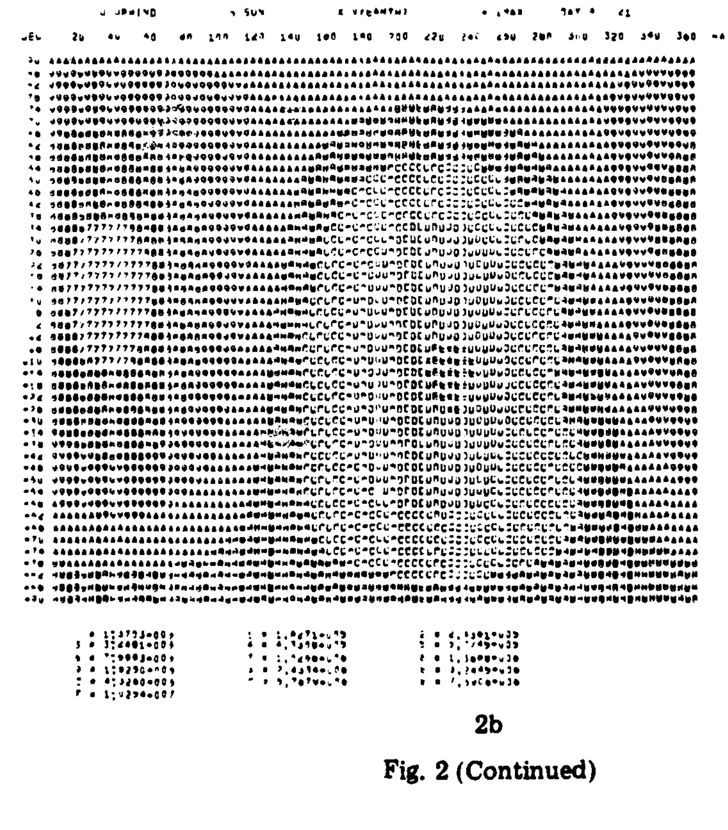



Fig. 2a—2s — Sky maps of intensity (above) and velocity (below). The vertical axis is declination and the horizontal axis (marked at the top) is right ascension. Details are described in the text.



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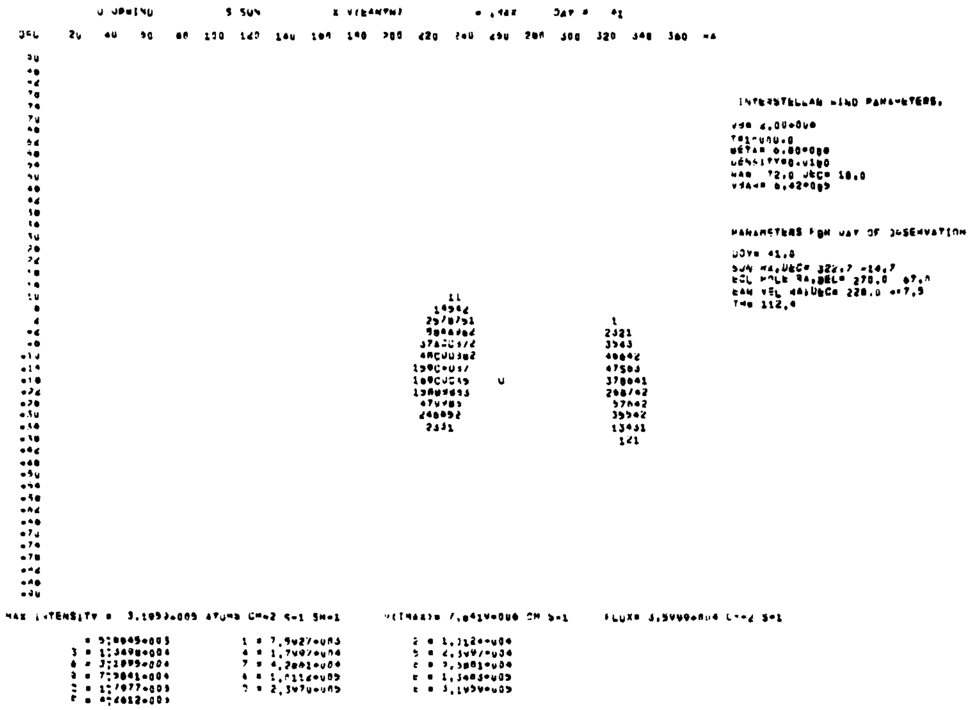


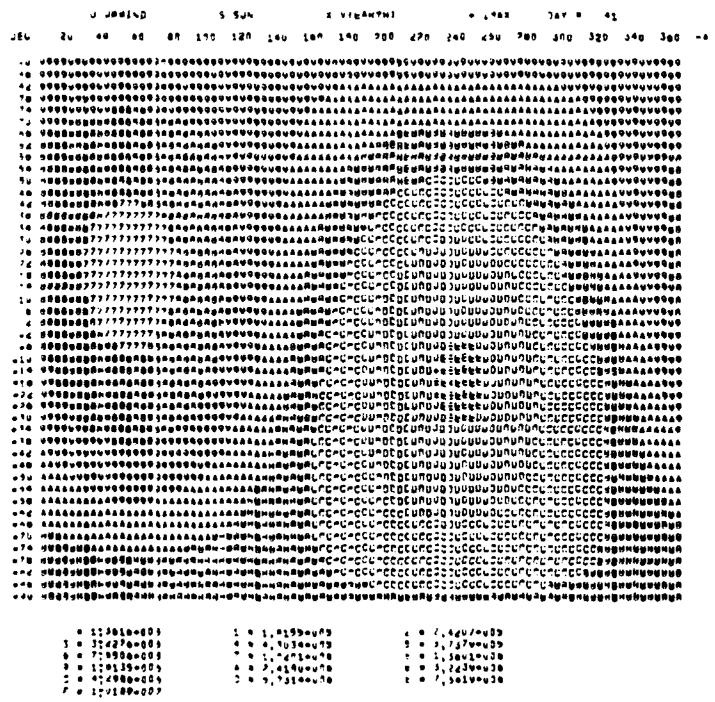

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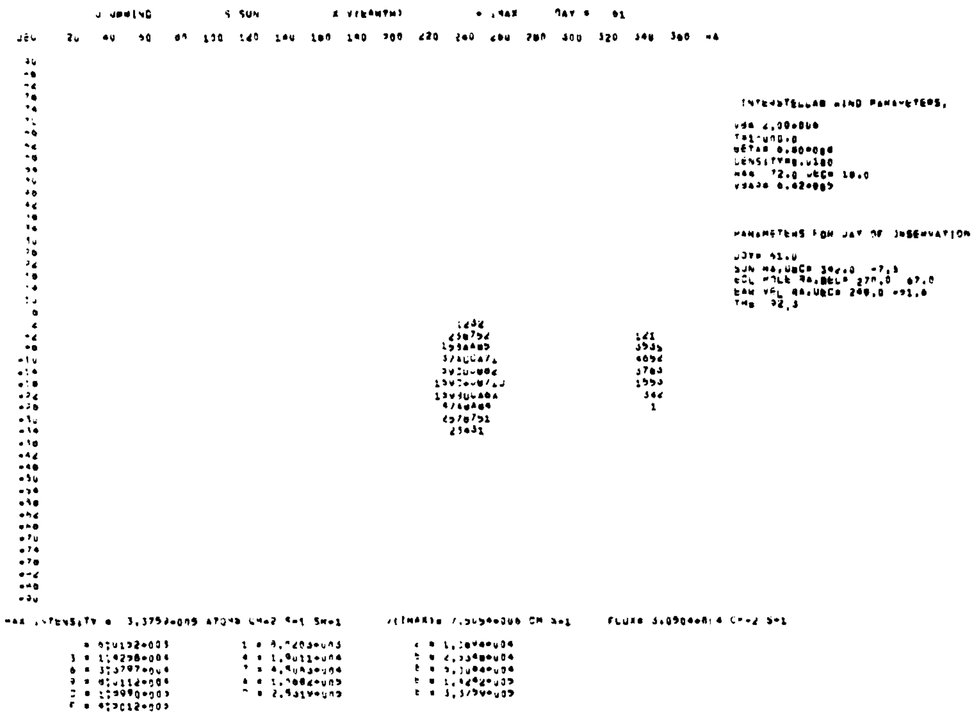

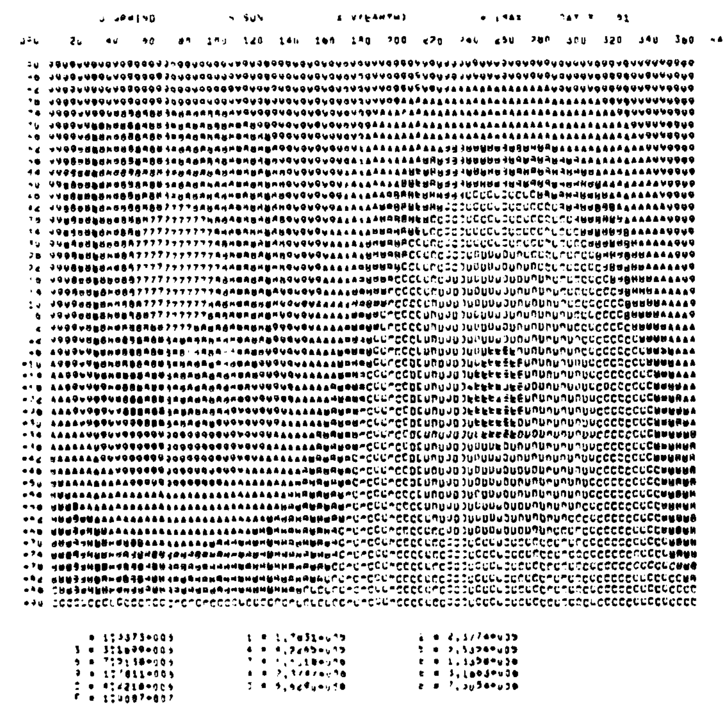

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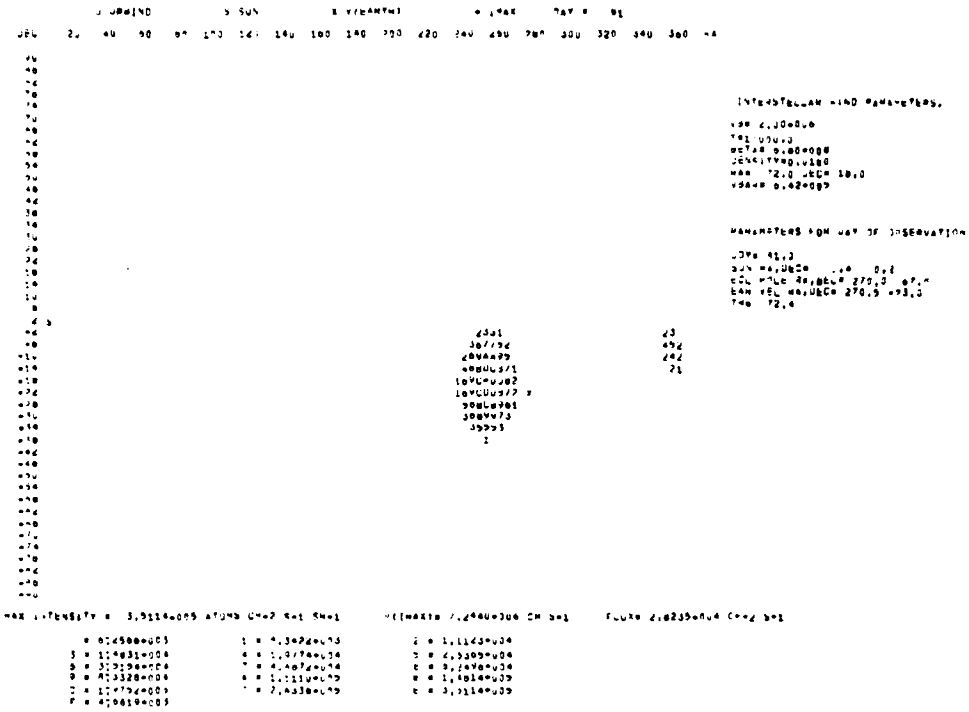


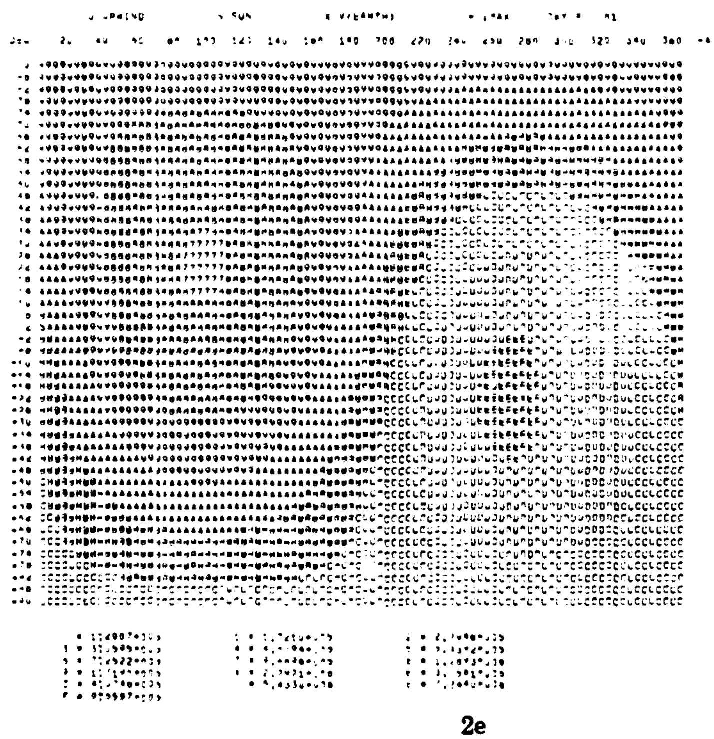

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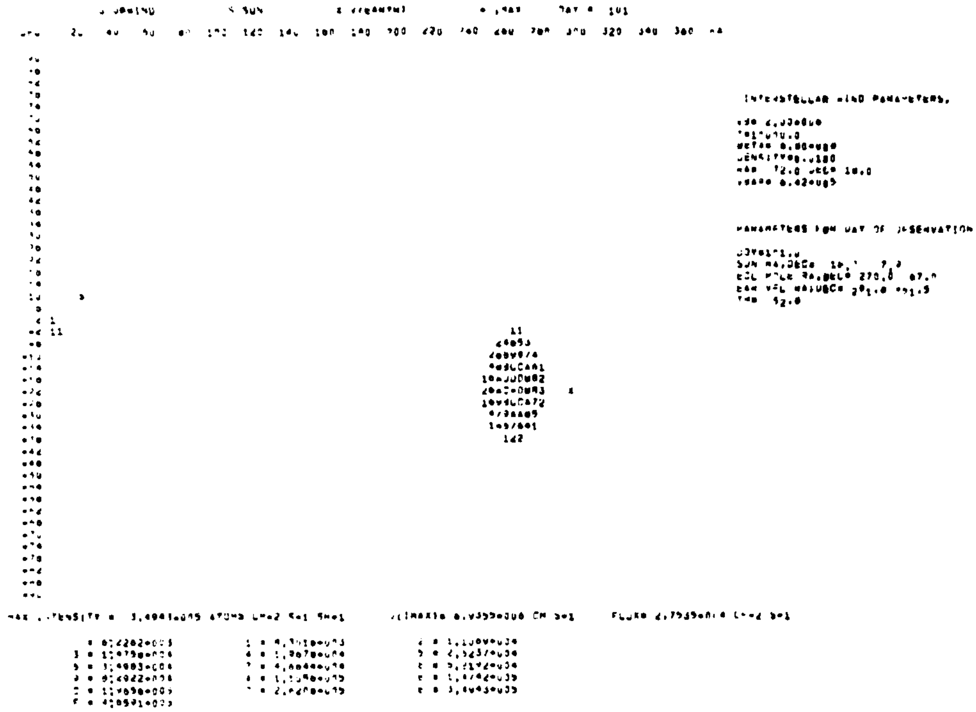

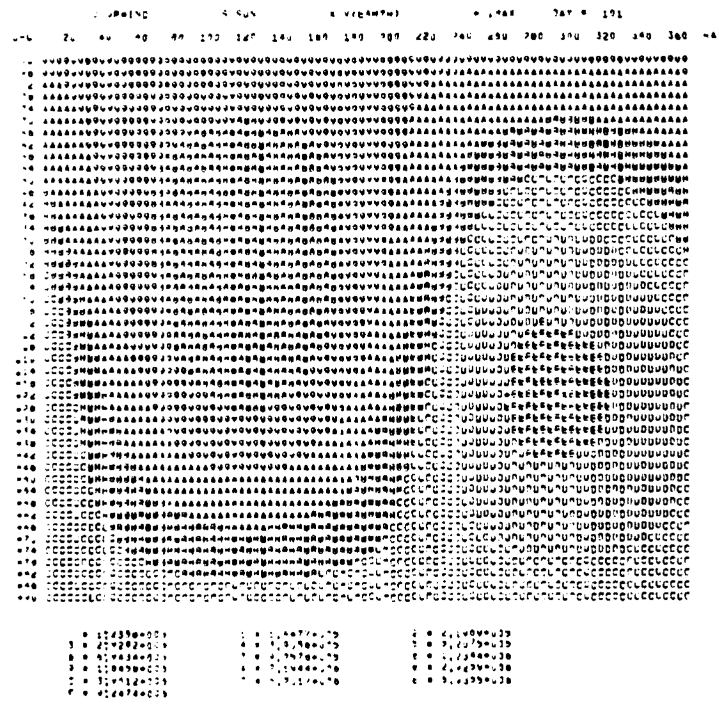

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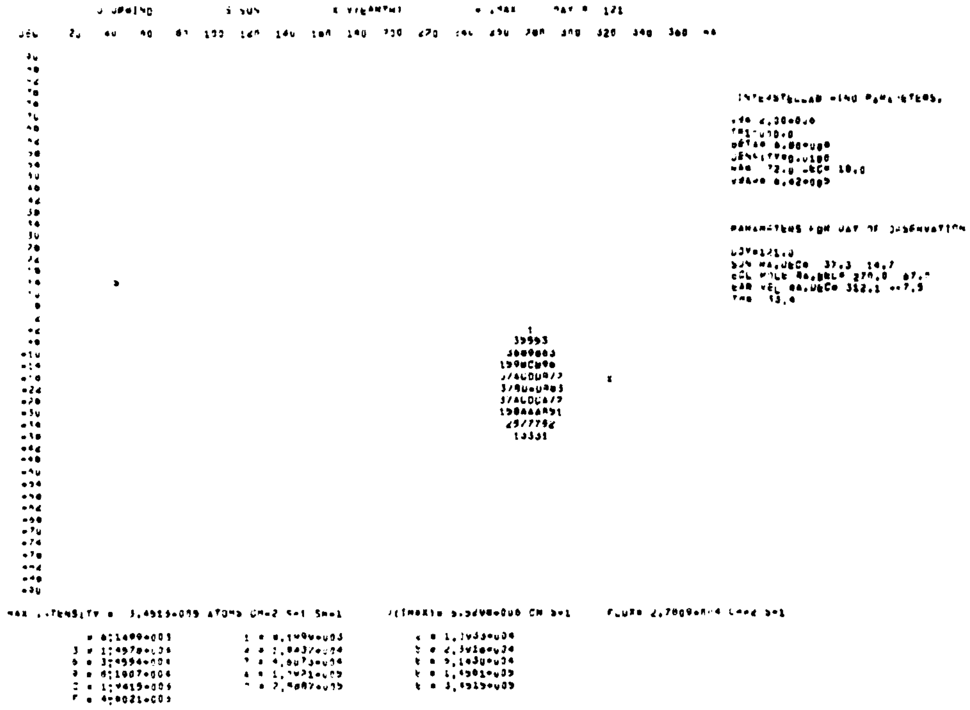

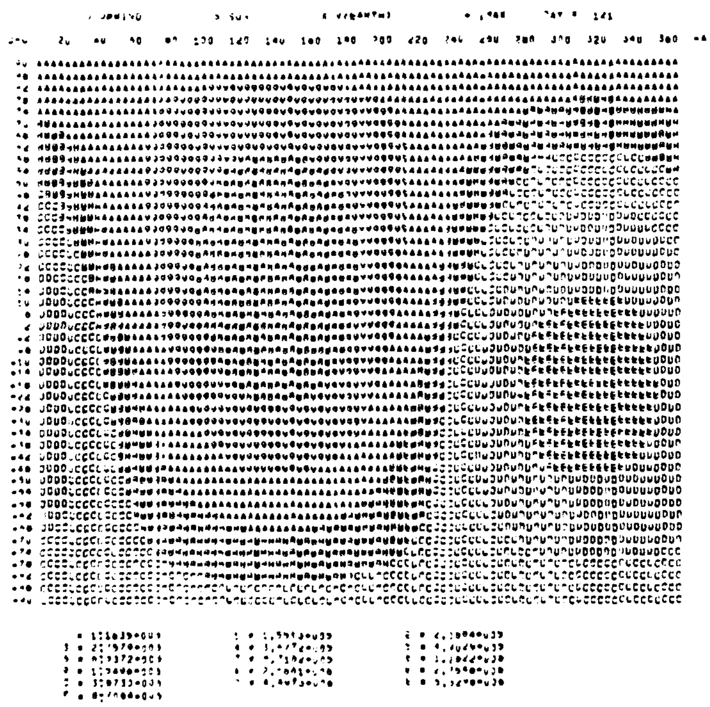

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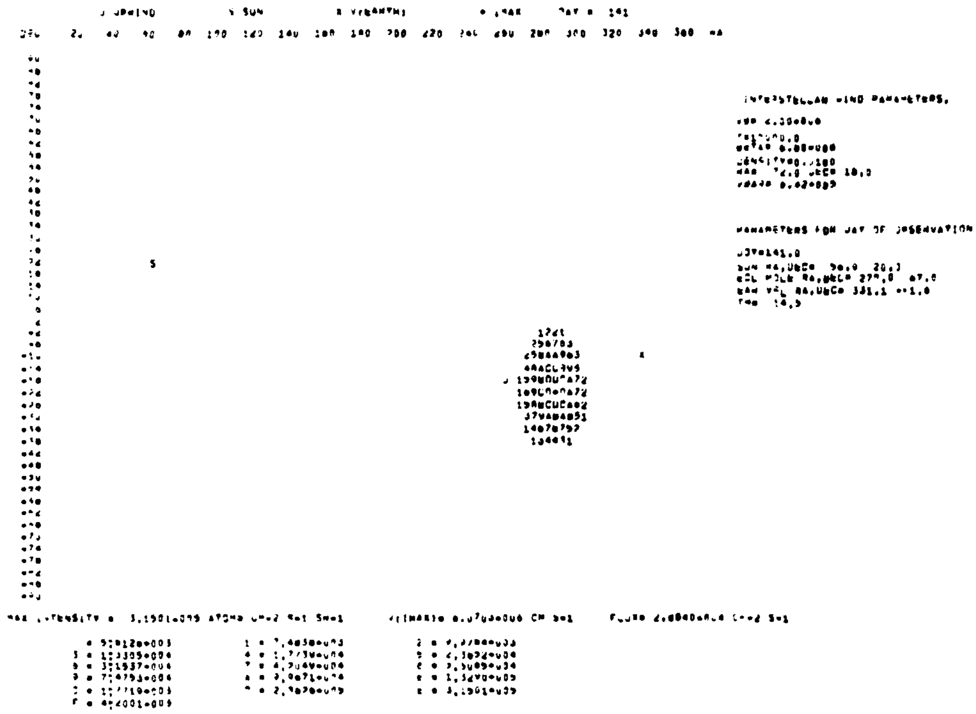

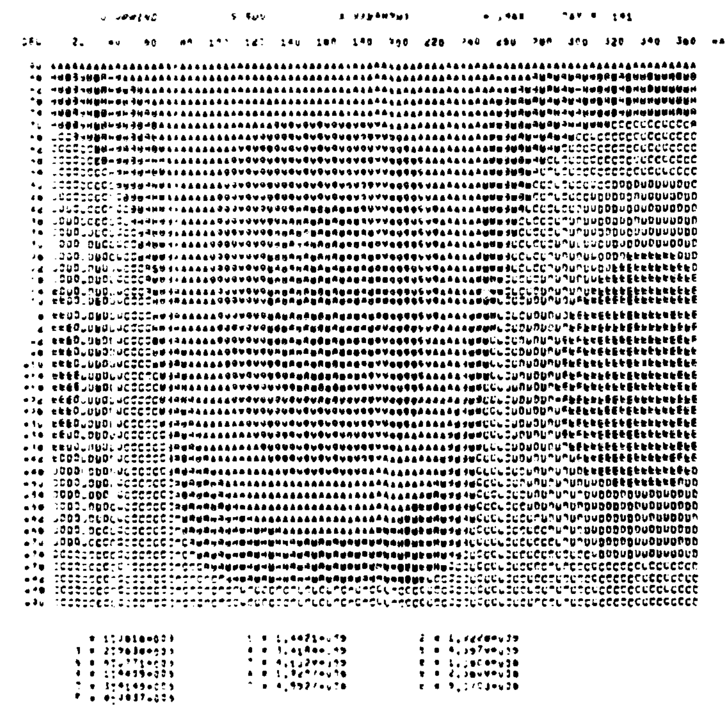

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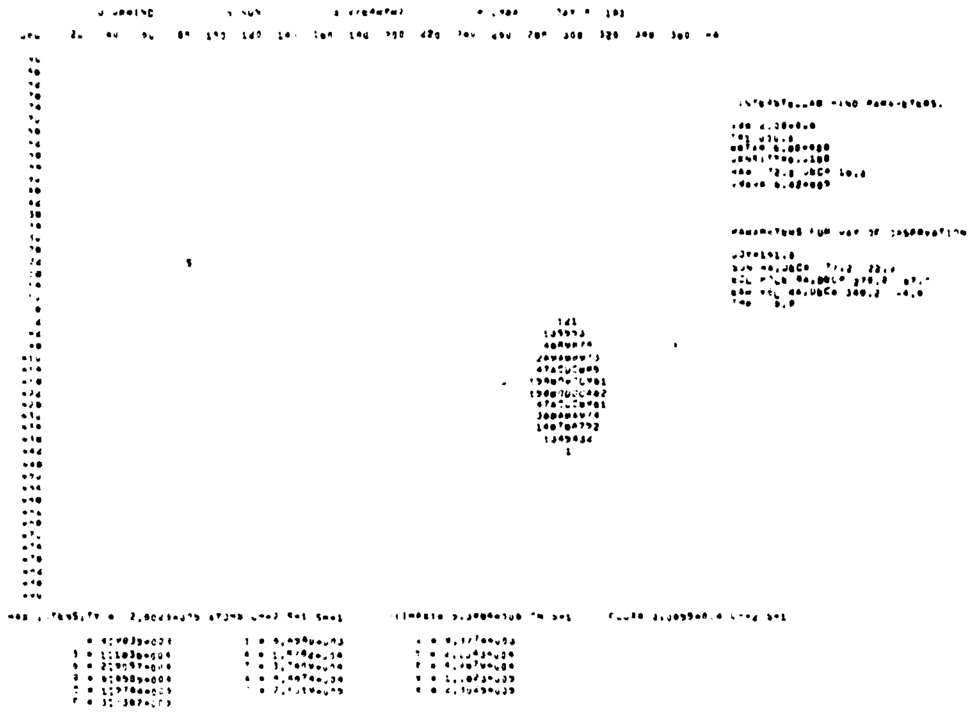

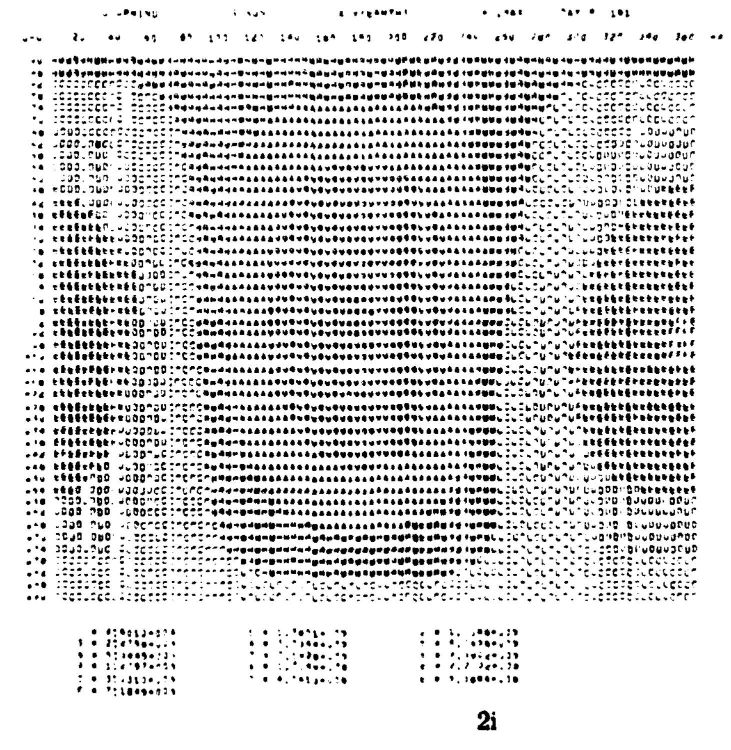

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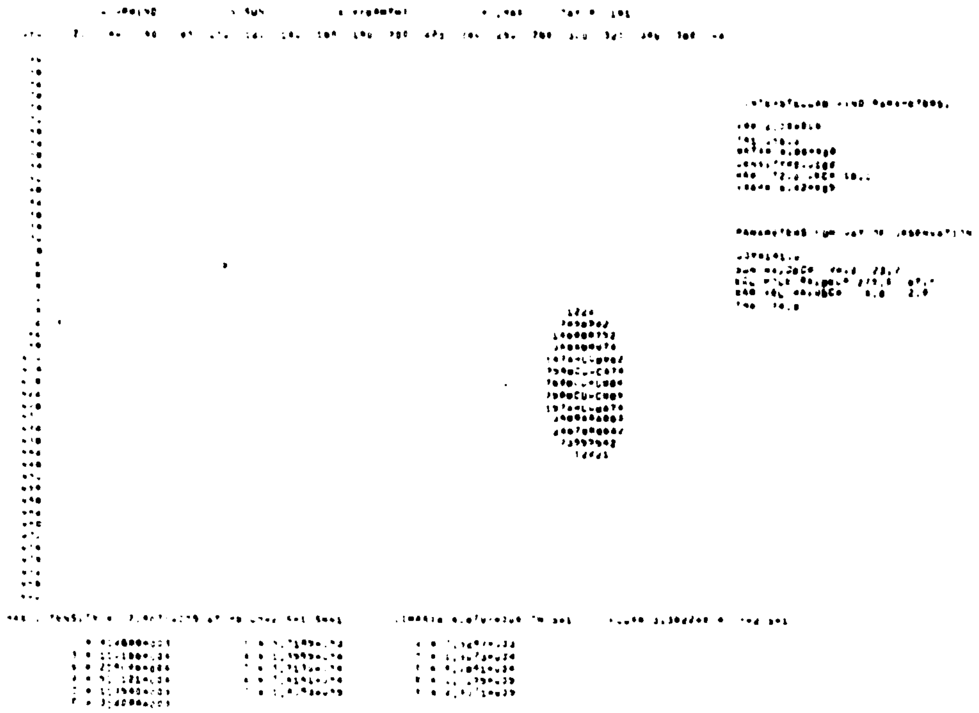

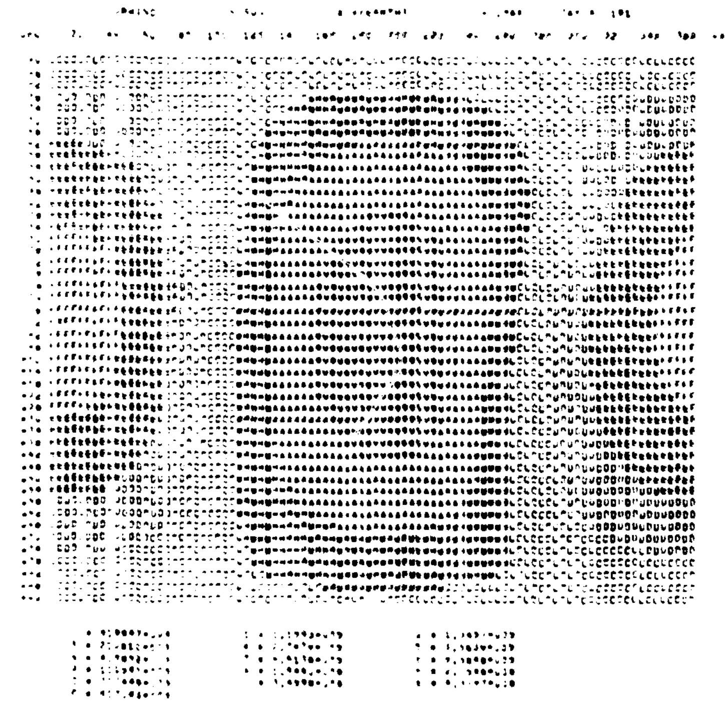

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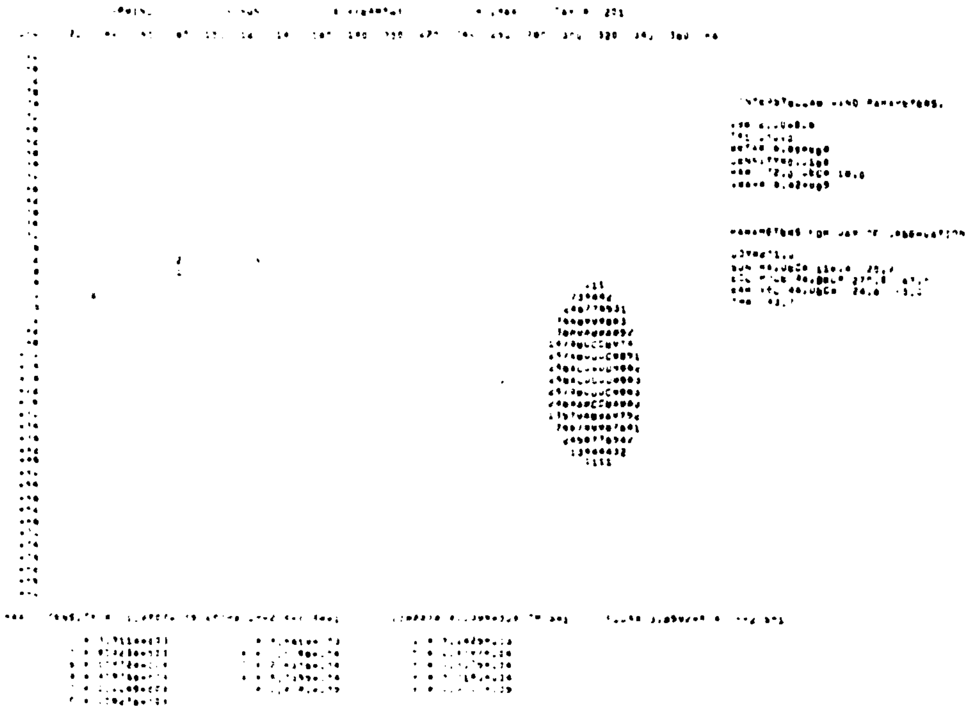

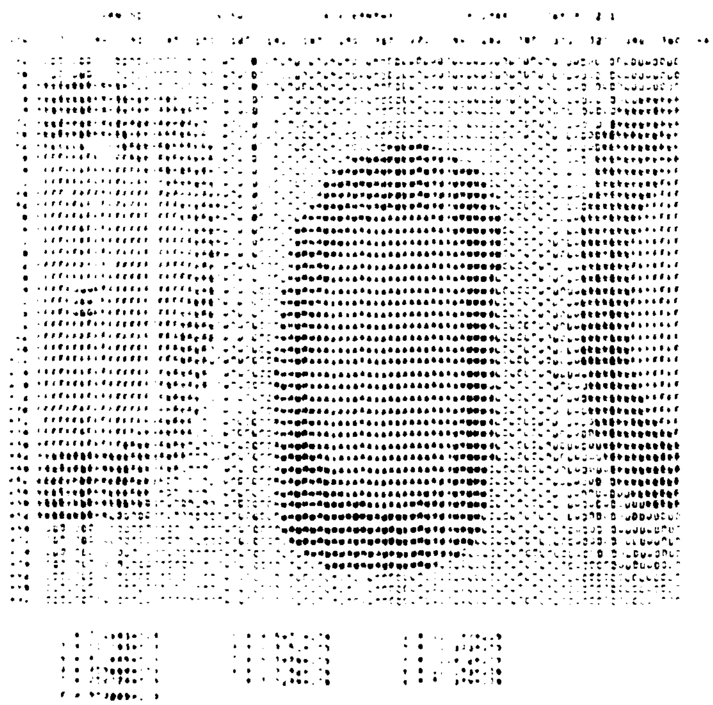

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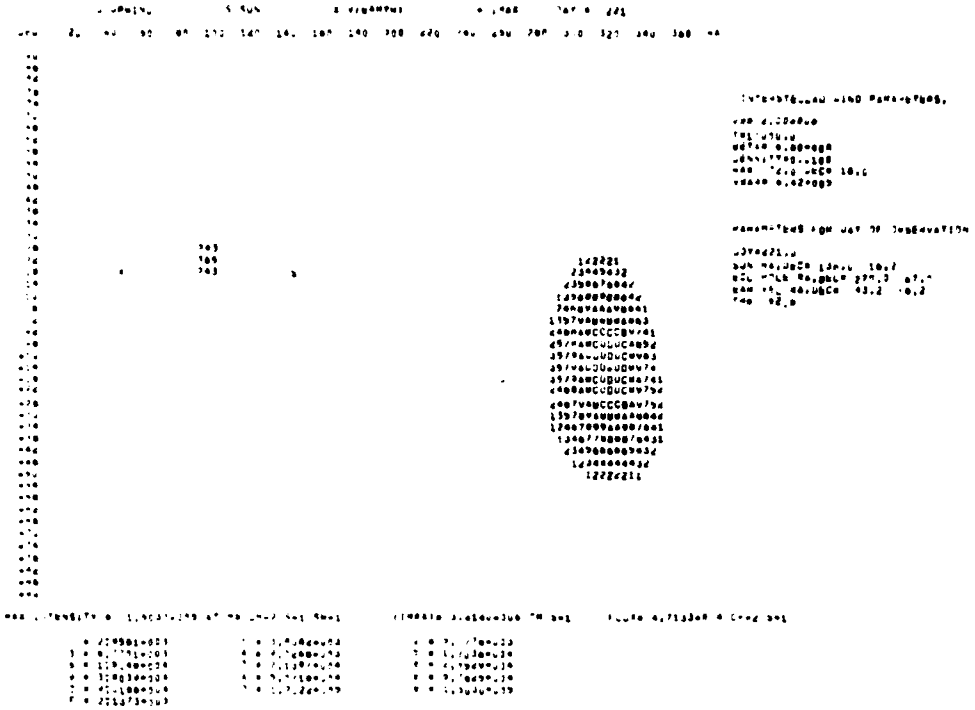

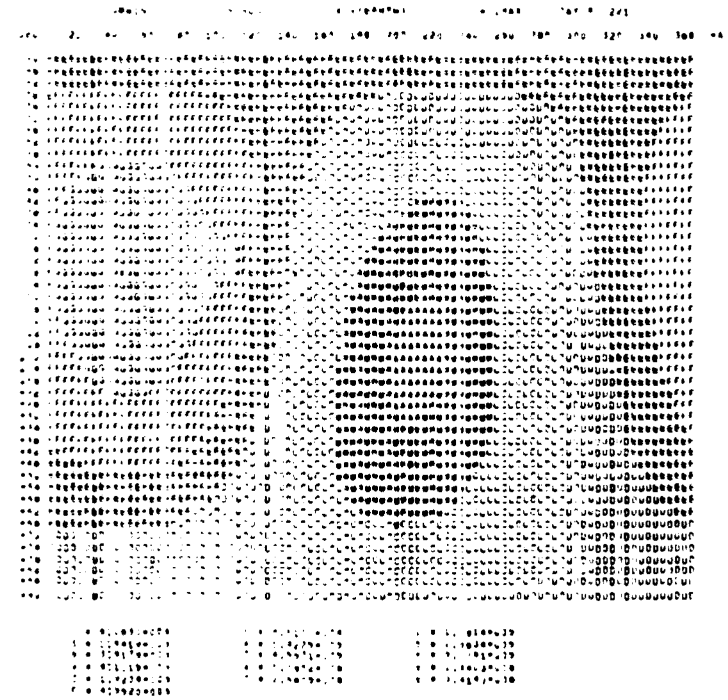

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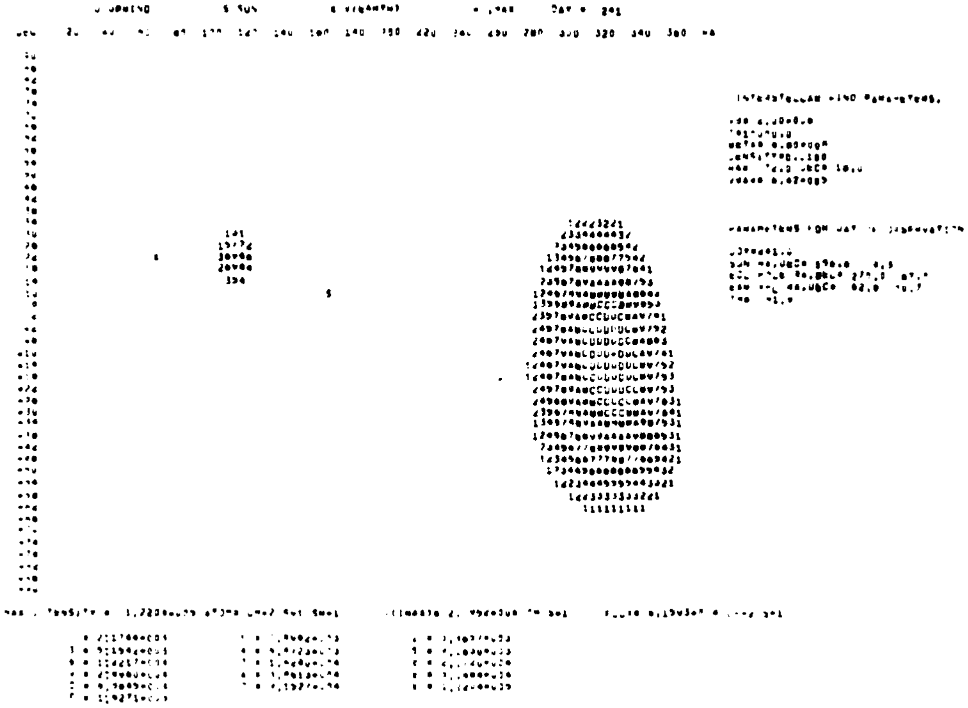

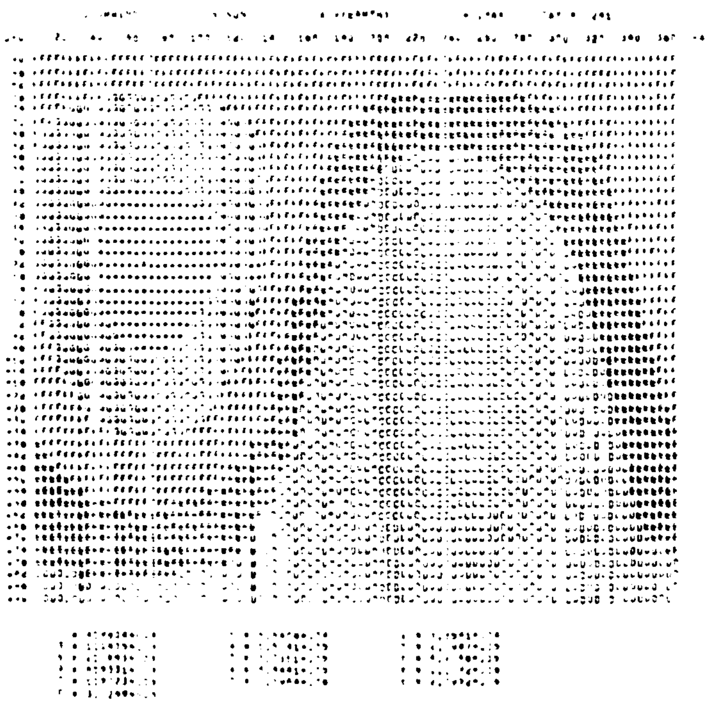

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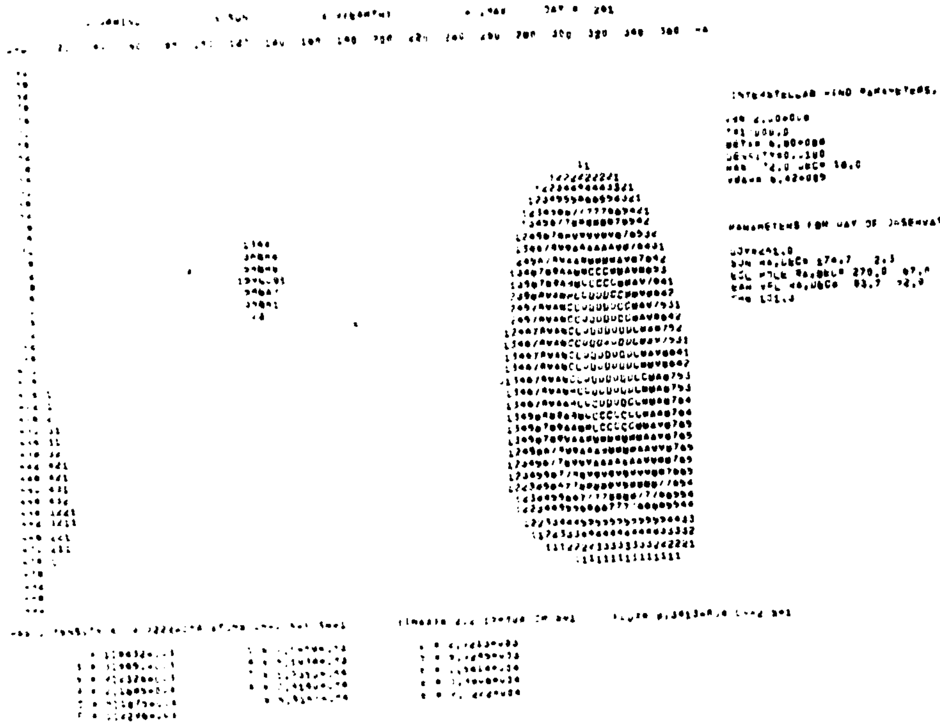

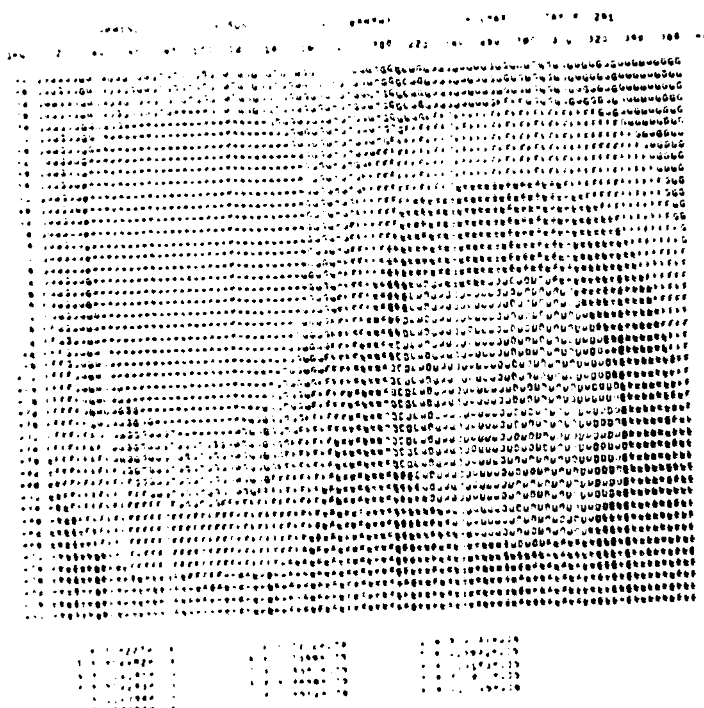

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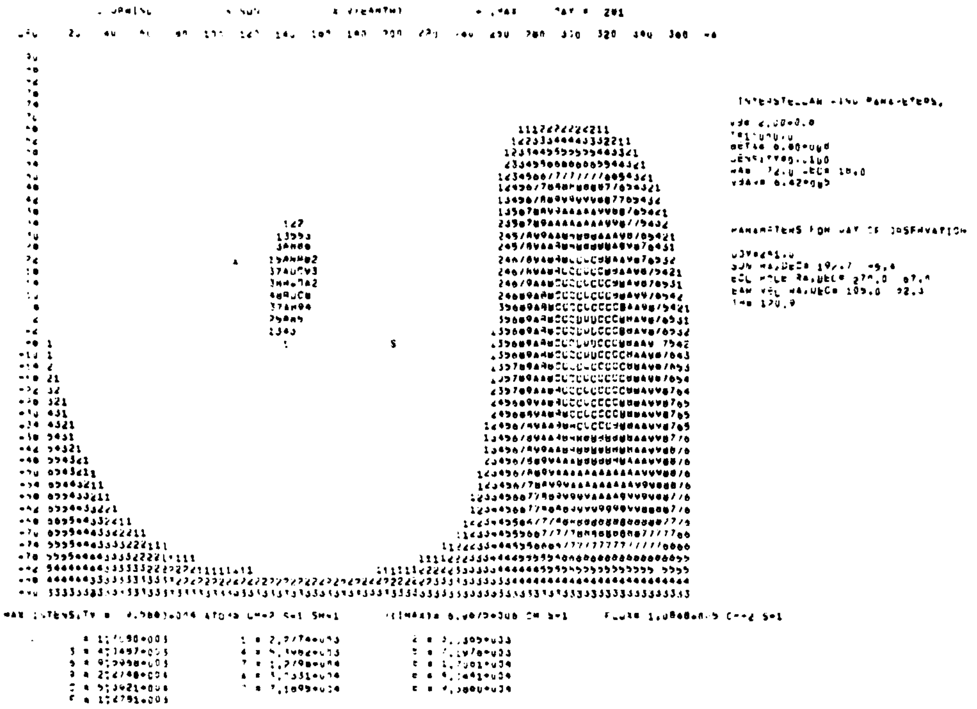

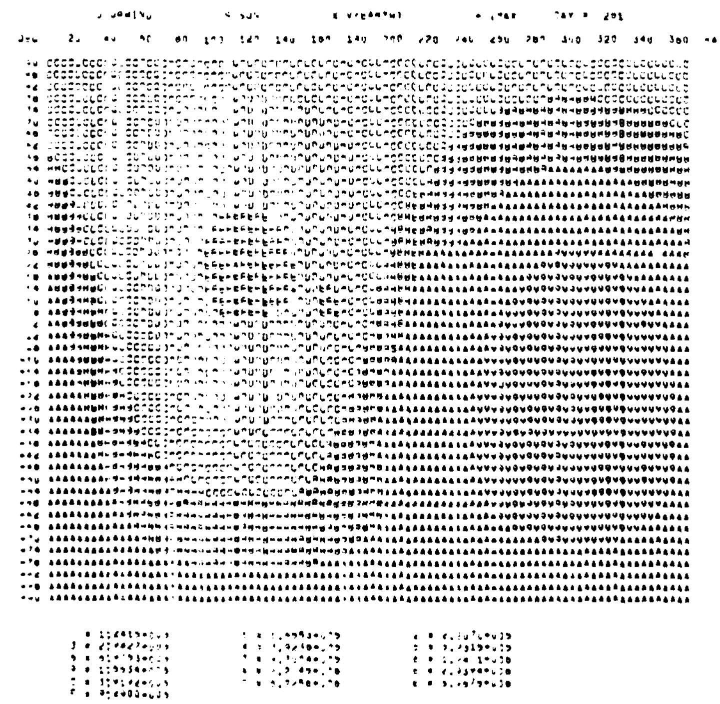

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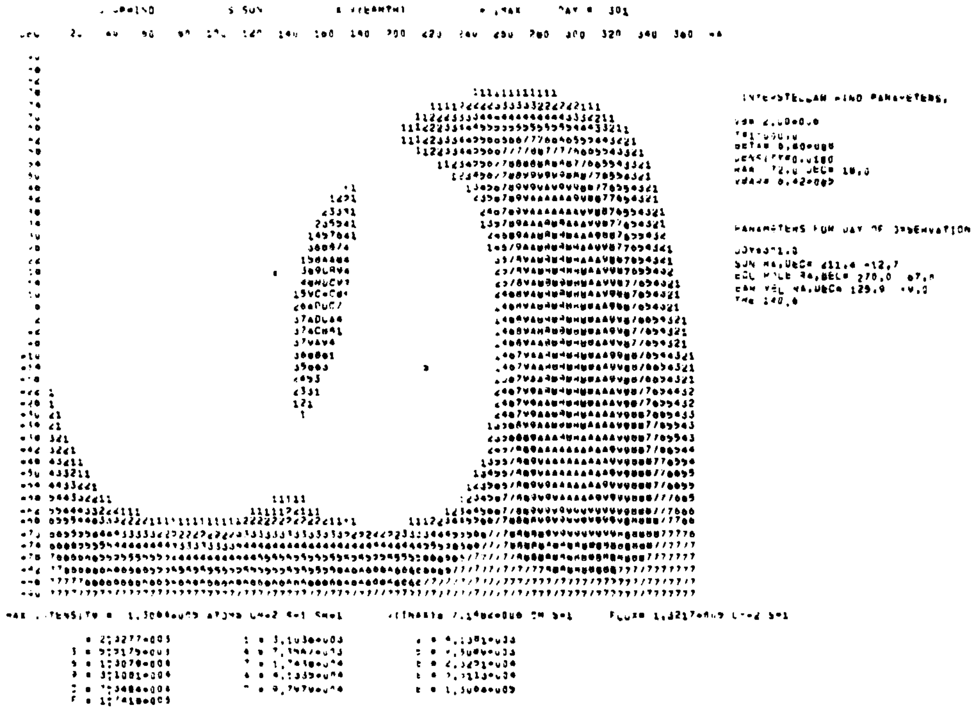


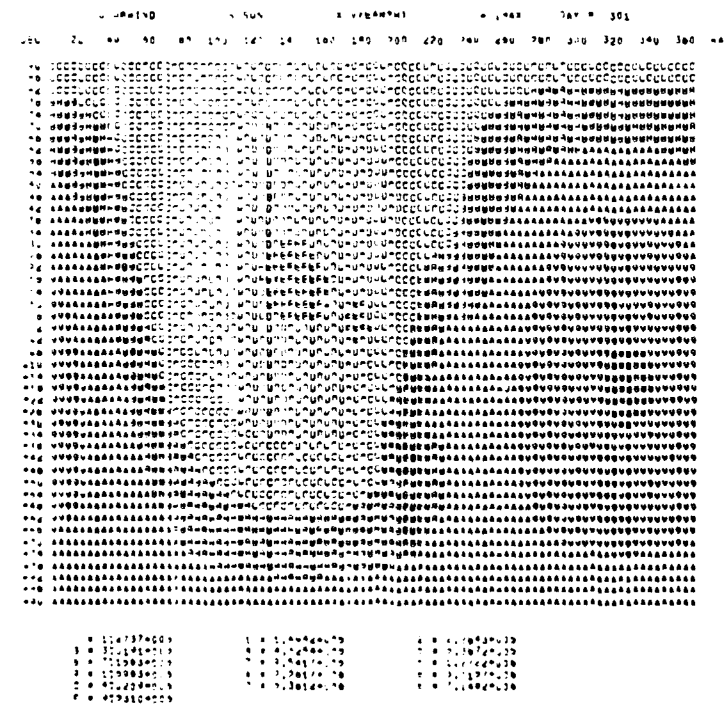

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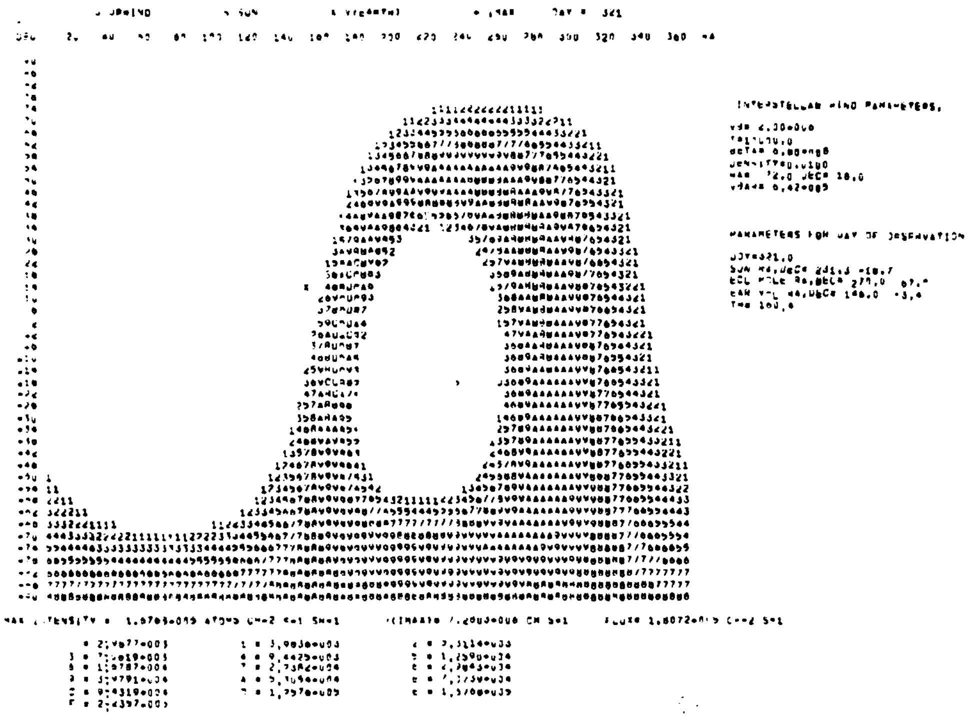


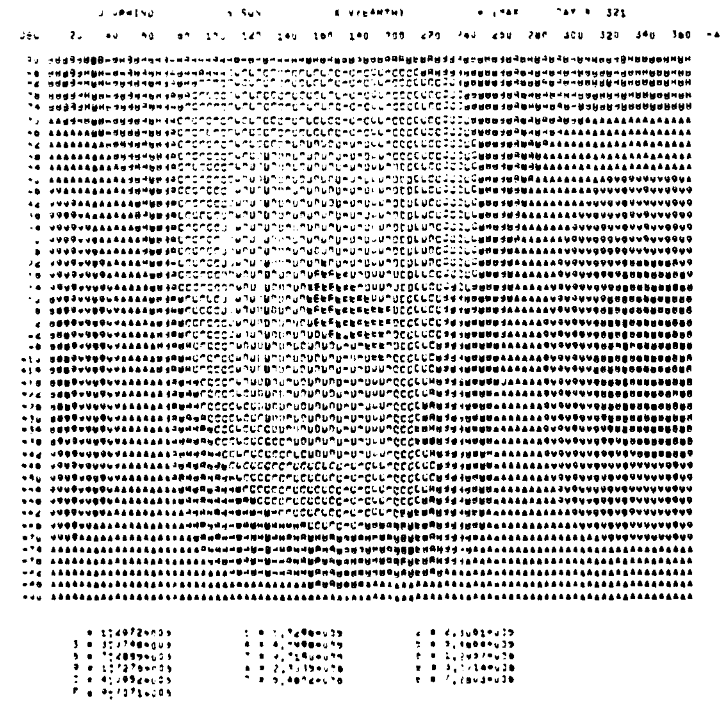

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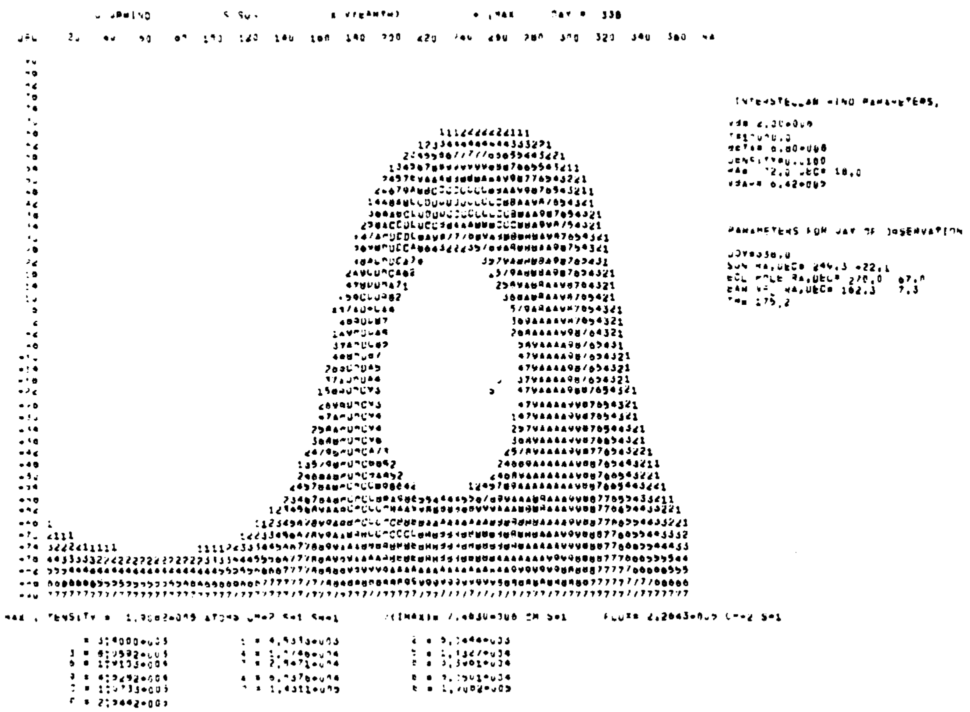

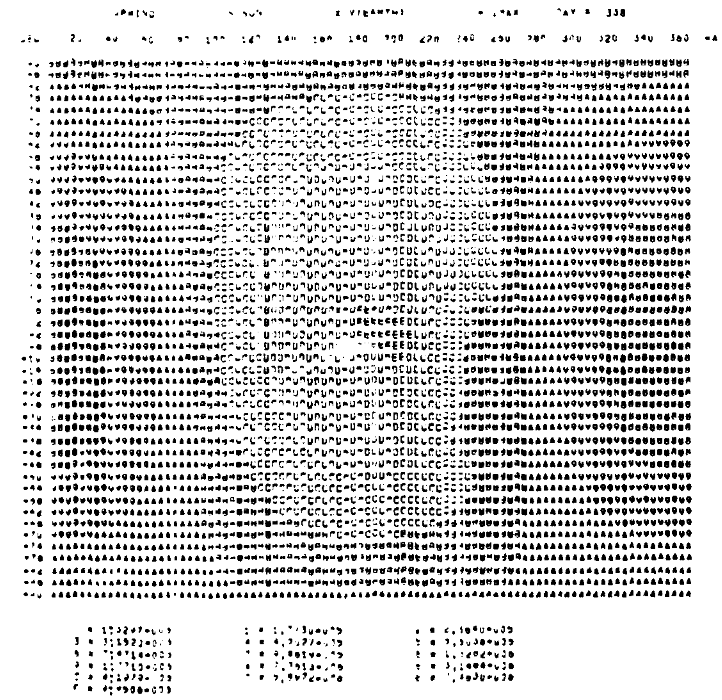

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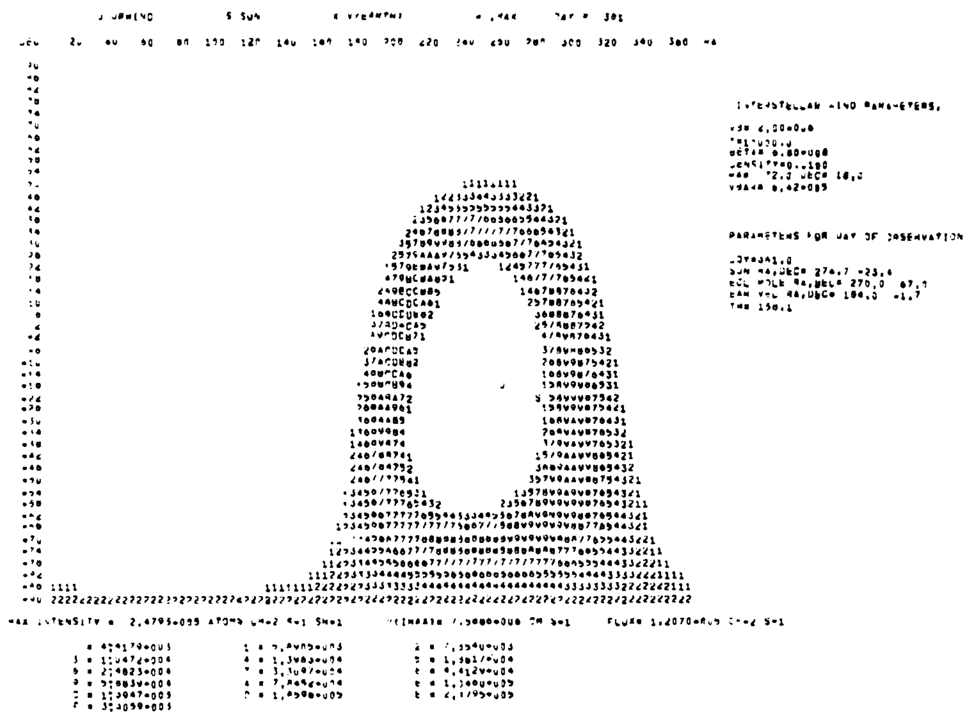

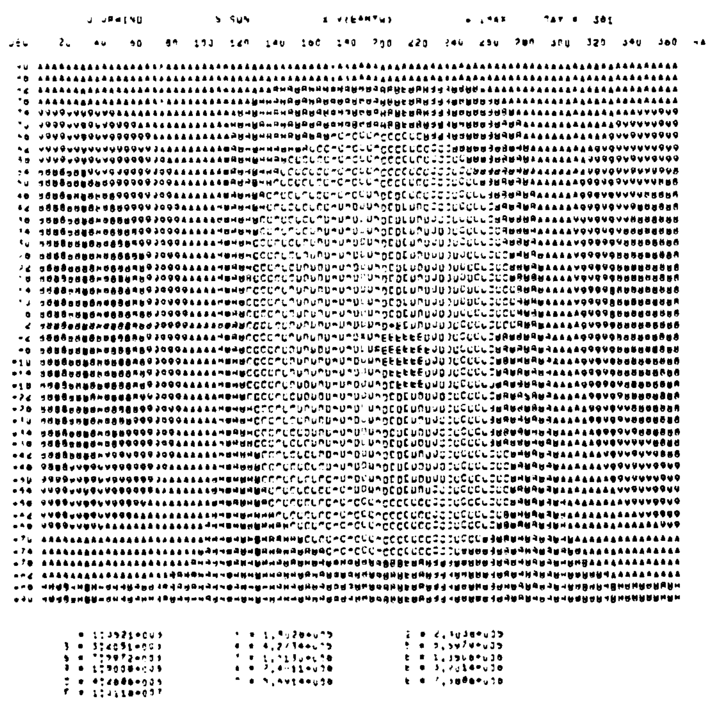

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The lower contour plot gives the mean velocity for all points in the sky. Since the $I_{max}$ position may not correspond to the highest velocity, the contour indicators can rise above "F".

The incoming interstellar wind direction (at infinity) relative to the solar system, the direction to the sun, and the earth velocity vector are indicated in the plots and given in the parameter lists. The parameters of the model for this display are chosen to be $v = 20$ km $s^{-1}$, T = 10,000K, ionization loss rate at 1 a.u. = 6.8 x $10^{-8}$ $s^{-1}$ and downstream direction $\alpha = 72°$, $\delta = 18°$, VBAR is the mean thermal velocity. DOY is the day-of-year and TH is the upwind-sun-earth angle.

The pattern seen for day 21 is a reasonably well-defined primary intensity distribution centered at α212 and δ-10 which is produced by the combination of 30 km $s^{-1}$ earth orbital velocity and helium atoms being directed along hyperbolas roughly parallel to the earth velocity vector. A secondary pattern is centered at α312 and δ-26, with peak intensity about a factor of 4 lower than the primary peak. The closest approach of the maximum particle flow to $\underline{v}_E$ occurs around day 21 (closest approach of the "x" to the "+". As the day-of-year increases, the intensity becomes more collimated, because the particle orbits are less dispersed by solar gravity. The absolute value of the peak intensity goes through a broad maximum around day 101 (see Figure 3). Throughout this period, the mean velocity in the direction of $I_{max}$ is in excess of 70 km $s^{-1}$, but begins to drop at day 121, reflecting the fact that $\underline{v}_E$ is moving away from $I_{max}$ and that $\underline{v}$ itself is lower because of less gravitational acceleration. The secondary pattern has now become too weak to show up on the contours.

Into summer, the intensity pattern broadens and in late summer/early fall the earth is moving in roughly the same direction as the interstellar gas. The velocity of $I_{max}$ drops to less than 20 km $s^{-1}$. In the meantime, atoms on acute hyperbolas (the so-called secondary component) have become evident in the velocity contours again near $\underline{v}_E$, since they have swung around the sun, gaining kinetic energy, and oppose the earth's motion. However, their intensity remains very low until day 221 when they appear on the contour plots as a small collimated beam. By day 301, the secondary component has become more intense than the primary component, which has spread out into a broad, diffuse pattern.

Throughout fall, the patterns of both components elongate and eventually merge together forming an asymmetric annulus. The asymmetry arises mainly due to the earth's velocity. A secondary cause of asymmetry occurs because the gas flow is not directed in the ecliptic plane. The closest approach of the earth to the downstream direction occurs on day 338 (about 5°). If the earth were motionless and exactly in the downstream direction, a symmetric annulus would be formed since the primary and secondary components are indistinguishable.

Around the beginning of the year, the annulus shrinks and separates into primary and secondary components again. Note that because the velocity distribution is modified Maxwell-Boltzmann the pattern is actually continuous across the sky throughout the year with primary peaks always present; however, often the secondary intensities (and those in-between the primary and secondary) are just too weak to show up on the contour graphs, which are limited to 1% of $I_{max}$.

The magnitudes, gradients, and positions of the intensity in the sky give sufficient information to uniquely determine the density, temperature, velocity, and ionization rate of interstellar helium. Direct measurement of the neutral particles eliminates an important uncertainty in the optical backscatter technique: the required knowledge of the solar 584A flux and its line profile.

## IV. DETERMINATION OF GAS PARAMETERS

Synoptic studies of the intensity were performed to delineate its dependence on the input parameters. In this section, details of the studies are given.

### 1. Absolute Magnitude

Figure 3 summarizes the seasonal variation of $I_{max}$ and $\bar{v}$ at $I_{max}$. The switchover from primary to secondary components occurs around the middle of October. The best times to measure the magnitude of the intensity are winter and spring. Not only does the highest value occur then, but also the mean velocity is high, so that about 100 eV per atom is available to trigger a detector.

### 2. Direction of $I_{max}$

The position in the sky of the maximum intensity is influenced by the earth's velocity and the magnitude and direction of the interstellar

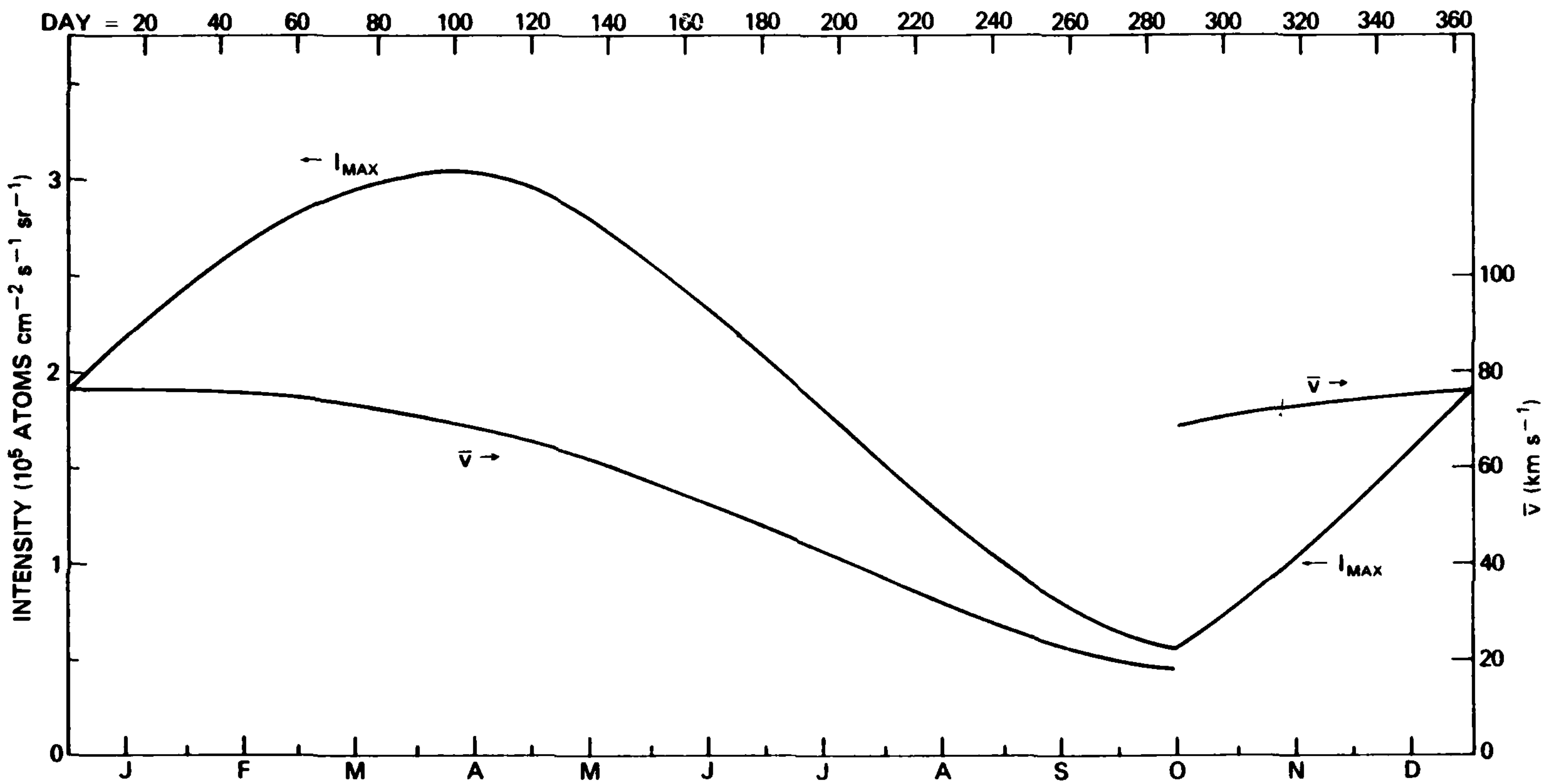


*Fig. 3* — $I_{max}$ *(left axis)* and v *(right axis)* vs. *day-of-year (upper axis)* and *month (lower axis)*. The large tic marks on the lower axis are for the 15th day of each month and the small tics are the beginning of the month.

bulk flow velocity at infinity. Calculations have shown that near day 121 the position of $I_{max}$ is essentially independent of the magnitude of $\underline{v}$, so that a measurement on that date gives the direction of the incoming gas relative to the solar system. However, since the earth velocity is large and combined vectorially with the gas velocity, a change of 6° in the direction of $\underline{v}$ translates to 3° in $I_{max}$. Thus, to reduce the present uncertainty of ± 3° in $\underline{v}$ as determined optically (Weller and Meier, 1980) to, say, ± 1°, the precision in determining $I_{max}$ should be of the order of ± 0.5°.

At other times of year, the position of $I_{max}$ depends on $|v|$ as well. Thus, if the direction of $\underline{v}$ is known, $|v|$ can be determined. For example, by changing $|v|$ from 15 to 25 km $s^{-1}$ (but keeping the direction fixed), the position of $I_{max}$ shifts by 7° in the sky on day 1, and by a similar amount on day 300. Thus, the magnitude of the bulk flow velocity vector can be determined from *position observations* at different times of year, independent of instrument calibration.

3. Pattern Size: T and v Dependence

During the spring and summer, the width of the intensity pattern depends both upon temperature and $|v|$. During periods when primary and secondary components are competing, the ionization rate also influences the pattern. However, since the ionization regime is about 0.5 a.u. in the upstream direction, $\beta$ has little effect there.

Figure 4 shows a plot of I versus right ascension for the declination which includes $I_{max}$, on day 60. Curves for three velocities and three temperatures are shown. It is clear that with a single

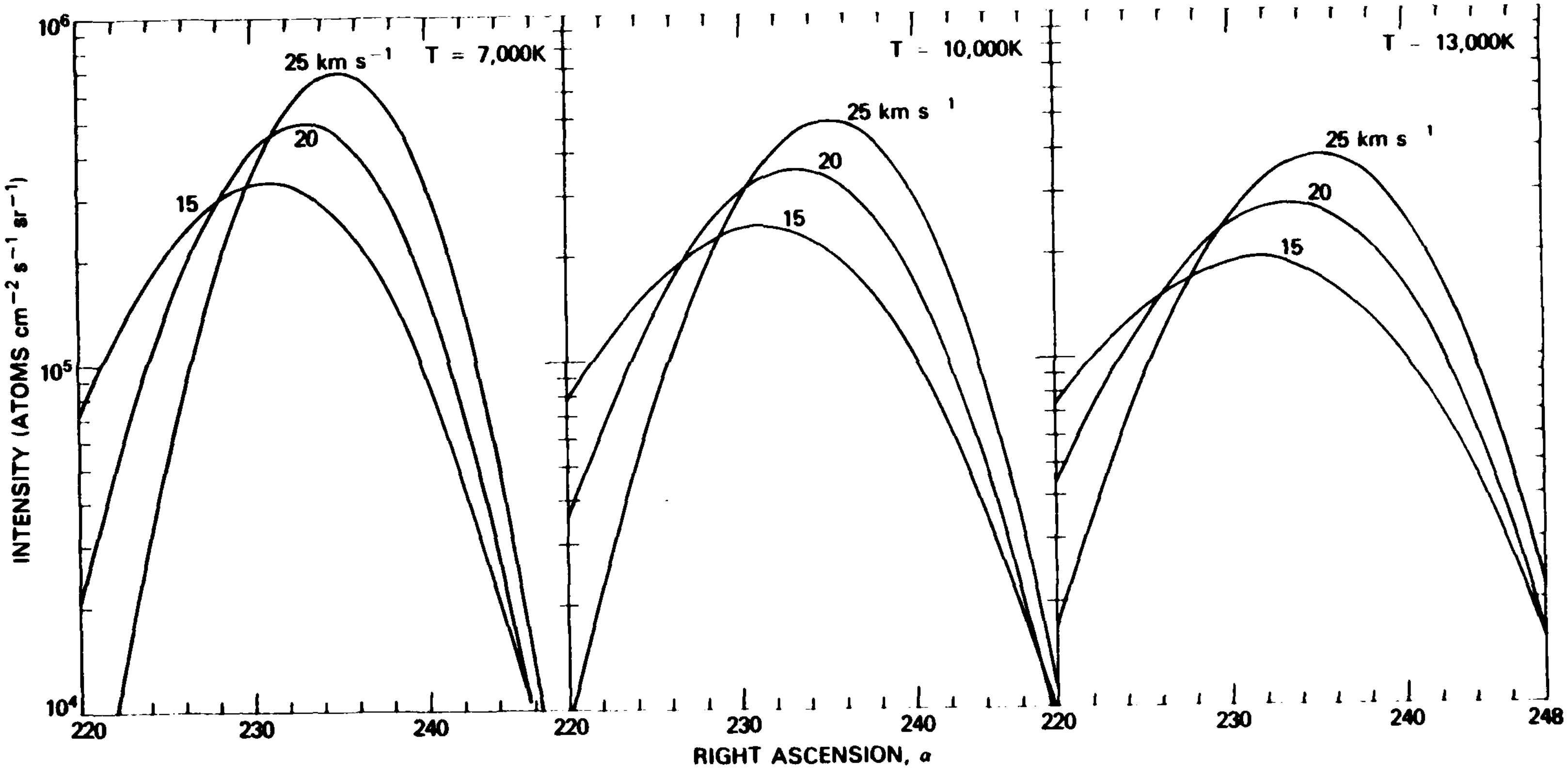


Fig. 4 — Intensity curves vs. right ascension for various velocities and temperatures for day 60. The declination in each case was chosen to pass through $I_{max}$

measurement, it is impossible to separate the influence of T from $|v|$. For example, T = 13,000K and v = 25 km $s^{-1}$ give the same intensity shape as 10,000K and 20 km $s^{-1}$. By making measurements at other times of year, the patterns show slightly different T and v dependences, but they are not likely to be distinguishable experimentally. As noted earlier, $|v|$ can be found if the gas direction is known. Thus, knowing the velocity, the temperature can be found from model calculations such as those in Figure 4, but measurement accuracy should be better than 1°.

4. Pattern Size: β Dependence

Photoionization of helium affects those intensities which are made up of atoms which have passed close to the sun. An example of this is shown in Figure 5 for day 301. In Figure 5a, primary and secondary components are seen for $\beta = 6.8 \times 10^{-8}$ $s^{-1}$. The secondary component is more intense with $I_{max} = 1.31 \times 10^5$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$. The primary component is more than a factor of two lower. Increasing β to $1.36 \times 10^{-7}$ $s^{-1}$ causes the maximum intensity to drop to $4.60 \times 10^4$ $cm^{-2}$ $s^{-1}$ $sr^{-1}$ with the primary and secondary peak being nearly equal in magnitude. However, the primary component has broadened somewhat. Since the contours on the individual plots are normalized to each $I_{max}$, the broadening is relative to $I_{max}$. In effect what has happened in 5b is that the overall magnitudes of I have dropped as well as a lessening of the gradient across the primary peak. Also, since β does not affect spring or summer intensities, the "upstream to downstream" intensity ratio is quite sensitive to the photoionization rate.

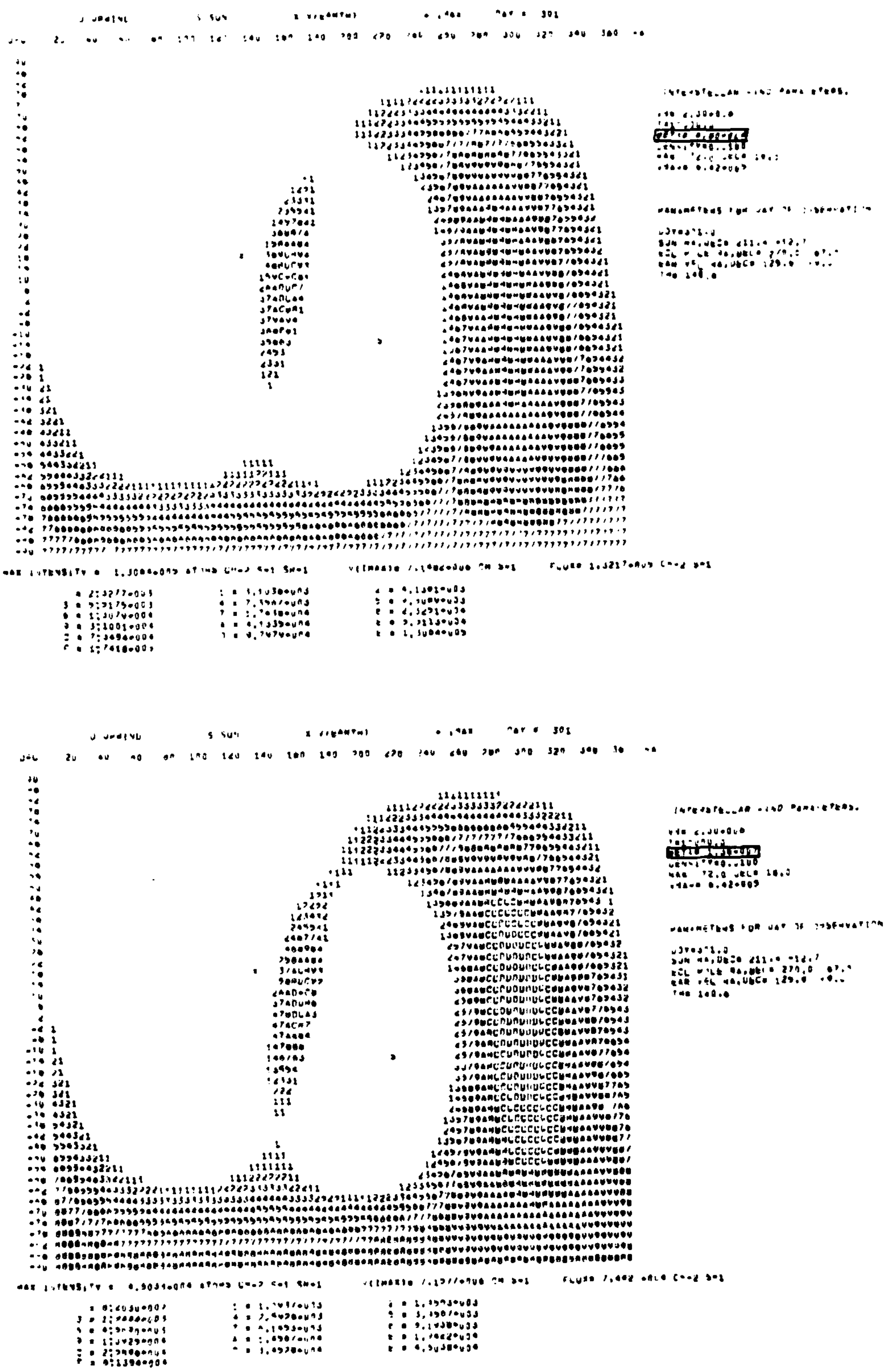

Fig. 5 — Comparison of intensity patterns on day 301 for $\beta = 6.8 \times 10^{-7}\ s^{-1}$ (upper) and $\beta = 13.6 \times 10^{-7}\ s^{-1}$ (lower)

Thus $\beta$ influences the primary to secondary intensity ratios as well as the size and magnitudes of the patterns (especially in the fall), and is quite sensitive to the intensity relative to other times of year.

## V. SUMMARY

It is clear from the discussion above that observations from the earth of the interstellar atomic helium intensity pattern can yield the density, temperature, velocity, and photoionization rate. Observations must be made at three different times of year to delineate all of the parameters. The angular resolution must be $< 1°$ for accurate spatial determination. However, an instrument with a well-known angular response could be used, even if its field of view is larger than 1°.

Several other caveats are important in considering neutral particle measurements. The experiment must be well above the atmosphere so that collisions do not degrade the incoming beam. Estimates of the effect are very uncertain, since the He + O differential cross section is not known (especially at small angles). Estimates using a He + Ar cross section indicate that the observing platform should be above 450-500 km to avoid significant perturbation of the incoming He. Another effect which may cause minor degradation of the beam is focusing by the earth's gravitational field (Fahr et al., 1976). However, for observations in the direction of the incoming helium this effect is negligible.

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