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TIME DEPENDENT EMISSION LINE PROFILES IN THE RADIALLY STREAMING PARTICLE MODEL OF SEYFERT GALAXY NUCLEI AND QUASI-STELLAR OBJECTS

by

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Abstract

The radially-streaming particle model for broad quasar and Seyfert galaxy emission features is modified to include sources of time dependence. The results are suggestive of reported observations of multiple components, variability, and transient features in the wings of Seyfert and quasi-stellar emission lines.

I. Introduction

A model has been proposed by Ptak and Stoner (Ptak and Stoner 1973 and Stoner, Ptak and Ellis 1974) which assumes that the broad components of the emission lines in Seyfert galaxies and quasi-stellar objects arise from radially moving suprathermal particles passing through an ambient, partially ionized region within the nucleus of the object. They have obtained theoretical profiles in good agreement with observations of several Seyfert nuclei and quasars. Their model, however, predicts smooth profiles which do not change with time.

Some high resolution spectra of Seyfert galaxies and quasi-stellar objects show fine structure in the broad emission lines. Burbidge and Burbidge (1966) have observed the appearance, disappearance and possible shifts in wavelength of emission components in the Mg II lines of 3C 345. Rubin and Ford (1968) have reported multiple components in Balmer line wings emitted by NGC 3227 in contrast with smooth, narrow forbidden lines in the same object. A blue shifted component of the balmer lines in Markarian 6 appeared on spectra obtained by Khachikian and Weedman (1971), but was not present on spectra taken less than a year prior to their observations. Pronik and Chuvaev (1972) observed the same feature on several occasions beginning in 1970 April, detecting changes in intensity and possibly also in the structure of the hydrogen lines. They also mention the possible existence of more fine structure in the emission wings near the resolution limit of their instrumentation. Cherepashchuk and Lyutyi (1973) have studied NGC 1068, 3516, and 4151 and conclude that rapid variations with a time scale of about a week are present in the hydrogen emission features of these objects. They suggest that 10 to 35% fluctuations arise in the wings of the hydrogen lines. Anderson (1974) has attributed the latter observations on NGC 4151 to a time-variable absorption feature.

In view of these reported observations, it is of interest to modify the time independent version of the radially streaming particle model to determine whether the observed fine structure and time variability could result from a version of the model in which a burst of particles or a series of such bursts replaces a constant flux. This paper develops the possible observable consequences of such a modification.

II. Model Development

If it is assumed that the emitting region is a shell of partially-ionized gas surrounding the particle source, the time variability is determined by three characteristic times: the time required for a photon to traverse the radius R_o of the ambient shell, the "stopping time" τ of a particle interacting with the shell after being injected with velocity v_o, and the duration of the initial burst of particles Δt_1. The first of these three characteristic times can be expressed as R_o/c and serves as a convenient unit of time in the mathematical development of the model.

The second characteristic time, the "stopping time", results from interactions of the suprathermal particles with the partially-ionized gas. It will be assumed in the following that the supra-thermal particle is a proton. It should be emphasized, however, that the nature of the time variability of the broad emission in any line emitted in this manner by any ion will be similar.

A proton losing energy via collisions with free electrons, when the velocities of the protons are substantially greater than the thermal velocities of the electrons, will do so at a rate

$$\frac{dv}{dt} = \frac{4\pi N_H e^4 f_i f_+ \ln\Lambda}{m_e M_p v^2}, \qquad (1)$$

(Shkarofsky, Johnston and Bachynski, 1966) where N_H is the heavy particle number density, f_i is the ionization fraction of the gas, f_+ is the fraction of time the streaming proton spends in an ionized state and $\ln\Lambda$ is the Debye screening factor.

The fraction f_+ is itself a function of velocity and of the ionization fraction f_i (see Ptak and Stoner 1973, figure 1). For simplicity, the velocity dependence of f_+ will be neglected. While this neglection is strictly appropriate only for $f_i \approx 1$, using the full velocity dependence of f_+ will change only the details of the emission line profiles and will have no important effect on the characteristic time-dependent features of the profiles.

In this approximation, then, equation (1) can be integrated to yield

$$t = \frac{m_e M_p \ln\Lambda}{12\pi N_H e^4 f_i \langle f_+ \rangle}(v_o^3 - v^3) \qquad (2)$$

and the characteristic stopping time is

$$\tau = \left(\frac{m_e M_p \ln\Lambda v_o^3}{12\pi N_H e^4 f_i <f_+>}\right) \bigg/ \frac{R_o}{c} \qquad (3)$$

in units of R_o/C.

The third characteristic time, the duration of the burst, Δt_1, can be interpreted in a number of ways. If the initial burst of particles is of short duration compared with the length of the observation (i.e. "exposure time" for a given spectrum), the duration parameter simply represents the duration of the burst. If the burst lasts longer than the observation interval, then Δt_1 will be the "exposure time". Similarly, a small dispersion in distribution of the particle energies in the initial burst can be represented by the same parameter, since the initial velocity dispersion would allow the particles to come to rest at different times, causing the event to be prolonged for some finite period.

As the streaming protons reach and begin to interact with the gas shell, they will emit characteristic line photons. The observed frequency of these line photons will be determined by the line-of-sight velocity of the emitting particles. Equation (2) gives the time dependent nature of the radial velocity of the emitting particle. Combining equations (2) and (3) gives an expression for the time required to slow from v_o to v,

$$T_1(v) = \tau\left(1 - \frac{v^3}{v_o^3}\right) . \qquad (4)$$

All photons emitted simultaneously within the shell will not be seen at the same time by the observer. Thus, the different travel times to the observer lead to another source of time dependence. If θ is the angle made with the line-of-sight axis of the shell, the time required for any photon to reach a common base plane from which all photons require equal times to reach the observer (see Figure 1) is

$$T_2(\theta) = \frac{R_o}{c}(1 + \cos\theta).$$

Letting $z = \cos\theta$ and setting $Y = \frac{\Delta\lambda}{\lambda} c$, the observed Doppler shift in velocity units, this time becomes, in units R_o/C,

$$T_2(Y,v) = 1 + \frac{Y}{v}. \tag{5}$$

If the time independent profile expression presented by Stoner, Ptak and Ellis (1974, equation (5)) is modified to include the time dependent effects discussed above, the profile function becomes

$$f(Y,t) = K\int_{|Y|}^{v_o} dv\, \frac{I(v)}{P(v)} \int_{t-\frac{\Delta t_1}{2}}^{t+\frac{\Delta t_1}{2}} dt\, \delta\left[t - \tau\left(1 - \frac{v^3}{v_o^3}\right) - \left(1 + \frac{Y}{v}\right)\right] \tag{6}$$

where $I(v)$ is the rate of photon emission and $P(v)$ is the rate of kinetic energy loss of the suprathermal particle. For reasons of simplicity, equation (6) is written in the limit of infinite mean photon absorption length Λ. This has the effect of eliminating the asymmetry in the time independent profile; the effect of including it here would be to depress all profiles on the redward side.

Detailed calculation of the ratio of functions $I(v)/P(v)$ (Ptak, Stoner 1973a) indicates that it can be replaced adequately by a Gaussian. Using atomic units of velocity (one atomic unit = 2188 km/sec),

$$\frac{I(v)}{P(v)} = C \exp\left[-\frac{(v-1.5)^2}{(.42)^2}\right] .$$

in the case of streaming protons.

The Dirac delta function under the integration in equation (6) allows the integral over time to be easily performed, with the result that the remaining integral over velocity has limits that depend on Y,t and the parameters τ and Δt_1. Specifically, the least upper bound and greatest lower bounds (v_1 and v_2) must be determined such that

$$\frac{v_1^4}{v_o^3} + v_1\left[\left(t - \frac{\Delta t_1}{2}\right) - \tau - 1\right] - Y = 0 \qquad (7)$$

and

$$\frac{v_2^4}{v_o^3} + v_2\left[\left(t + \frac{\Delta t_1}{2}\right) - \tau - 1\right] - Y = 0 . \qquad (8)$$

Then, if v_1 is greater than $|Y|$, it becomes the lower bound of integration and similarly, if v_2 is less than v_o, v_2 becomes the upper bound. The profile function now becomes

$$f(Y,t) = k\int_{v_\ell}^{v_u} \exp\left[-\frac{(v-1.5)^2}{(.42)^2}\right] dv \qquad (9)$$

where v_ℓ and v_u are determined as described above. Equations (7) and (8) guarantee that the only photons observed at Y during the observation interval Δt_1 will arise from a streaming particle of the appropriate line-of-sight velocity and distance relative to the observer.

It should be noted that the single burst model developed above can be easily modified to account for multiple, periodic bursts of particles, in which case a fourth characteristic time, Δt_2, is introduced to represent the time between bursts. The resulting profile is then the superposition of several single burst profiles observed at times $t = 0$, Δt_2, $2\Delta t_2$, etc.

III. Results and Discussion

By numerically evaluating the profile function derived above, it is possible to generate theoretical emission profiles for the different values of the free parameters. The results which follow were obtained by evaluating equation (9) at one hundred evenly spaced values of Y such that $|Y| \leq v_o$. The roots of equations (7) and (8) were obtained numerically by the Newton-Cotes method and equation (9) was evaluated by Simpson integration. In all cases, v_o, the initial particle velocity was taken to be three atomic units.

When the value of τ is small compared to the photon traversal time (R_o/c), the "slowing down" time makes little contribution to the profile time dependence, and the geometric factors governing the line photon's transit time determine the profile evolution. Emission first appears blueward of the line center (zero Doppler shift in the rest frame of the ambient gas) and, as time progresses, it migrates redward, growing and decaying in a roughly symmetrical fashion (figure 2). Increasing the parameter Δt_1 tends to broaden the profile, but the general characteristics remain essentially unchanged; as Δt_1 approaches zero, the peaks on the blue side become singular point infinities.

For values of τ approaching the photon traversal time, the near symmetry about the line center is removed as the velocity dependence in equation (4) begins to have an effect. At early times, while the line is still on the blue side of center, it appears narrow and sharply peaked. Later, as the feature begins to decay, the profile becomes much smoother and somewhat broader (figure 3).

As the value of τ becomes larger than unity, a greater range of line-of-sight particle velocities is simultaneously observable. The profile from a single burst becomes broader as a result (figure 4). The superposition envelope representing a series of bursts appears much smoother than in the two previous examples.

The effect of increasing the number of bursts (reduction of the parameter Δt_2) for the $\tau = 1$ case is shown in figure 5. The blue wing of the resulting profile shows numerous discrete components while the red side remains smooth and featureless. A single, blue-shifted component can be generated by decreasing the number of bursts in the large τ case (figure 6). Similar types of fine structure are observed in the wings of some Seyfert galaxy nuclear emission lines.

To date, most explanations for fine structure in Seyfert galaxy and quasi-stellar emission lines have postulated mass motions within the object's nuclear region. If this approach is applied to emission profiles with multiple components in the wings, it implies the existence of discrete clouds with different radial velocities. The results presented here demonstrate that a stationary, partially ionized cloud surrounding an active region can produce the kind of fine structure that is observed. If an attempt is made to apply the single burst version of the present model to a transient blue shifted component, an observer should expect to see a redward migration before extinction. If there are several components in an emission profile, such as is depicted in figure 6, repeated, burstlike activity of the particle source is implied. Observations of variability in the radio and in the optical continuum of such objects seem consistent with repeated bursts of high energy particles, as do some models for the sources of their energy. Further observations of blue-shifted components like those seen in Markarian 6 in order to determine the evolution of such features would be quite useful in this regard.

The multiple component wings suggested to be present in many objects would be neatly explained by the present model with either periodic or random activity of the particle source. It should be noted, however, that according to the model presented here, the components tend to be a feature of the blue wings, while the red side of the profile remains smooth (Figure 5). The "valleys" between emission peaks may possibly simulate the apparent absorption dips on the blue side of emission wings for some objects. Again, high-resolution, low noise observational profiles are needed to determine the detailed appearance and stability of these features.

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Figure Captions

Figure 1. Illustration of the geometry of the model and of the origin of time variability arising from photon travel times. See text.

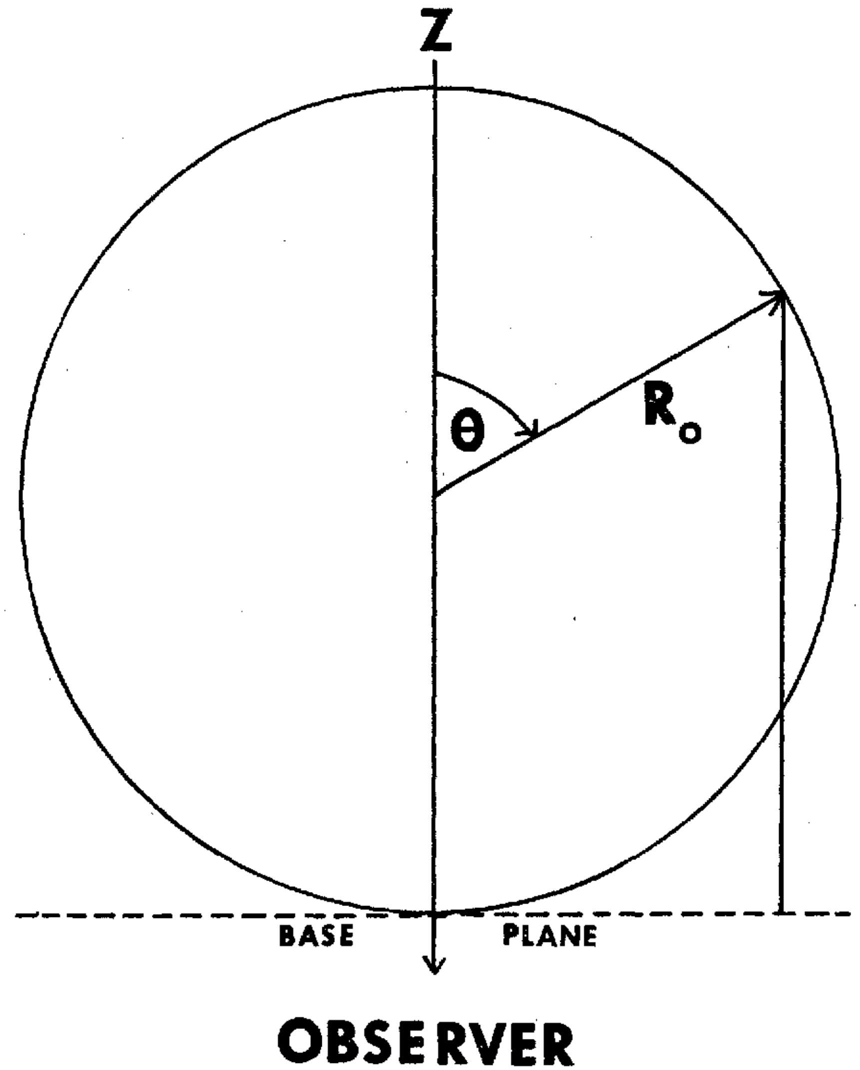
Figure 2. Theoretical profiles for $\tau = 0.1$ and $\Delta t_1 = 0.1$. Broken lines and central spikes are single burst profiles at eleven evenly spaced values of t from zero to $2 + \tau$. The $t = 0$ profile is insufficiently intense to appear. The solid line is the superposition envelope representing multiple bursts for $\Delta t_2 = 0.21$.

Figure 3. Theoretical profiles and the superposition envelope for $\tau = 1$, $\Delta t_1 = 0.1$ and $\Delta t_2 = 0.3$. The profiles at $t = 0$, 0.3, 0.6, and 3.0 are insufficiently intense to appear on the same scale.

Figure 4. Theoretical profiles and the superposition envelope for $\tau = 10$, $\Delta t_1 = 1$ and $\Delta t_2 = 1.2$. The first five profiles through $t = 4.8$ are too dim to appear on this scale.

Figure 5. Multiple components produced by a series of particle bursts with $\tau = 1$, $\Delta t_1 = 0.1$, $\Delta t_2 = 0.15$.

Figure 6. A single, blue-shifted component produced by the superposition of a series of seven particle bursts with $\tau = 10$, $\Delta t_1 = 1$, and $\Delta t_2 = 0.65$.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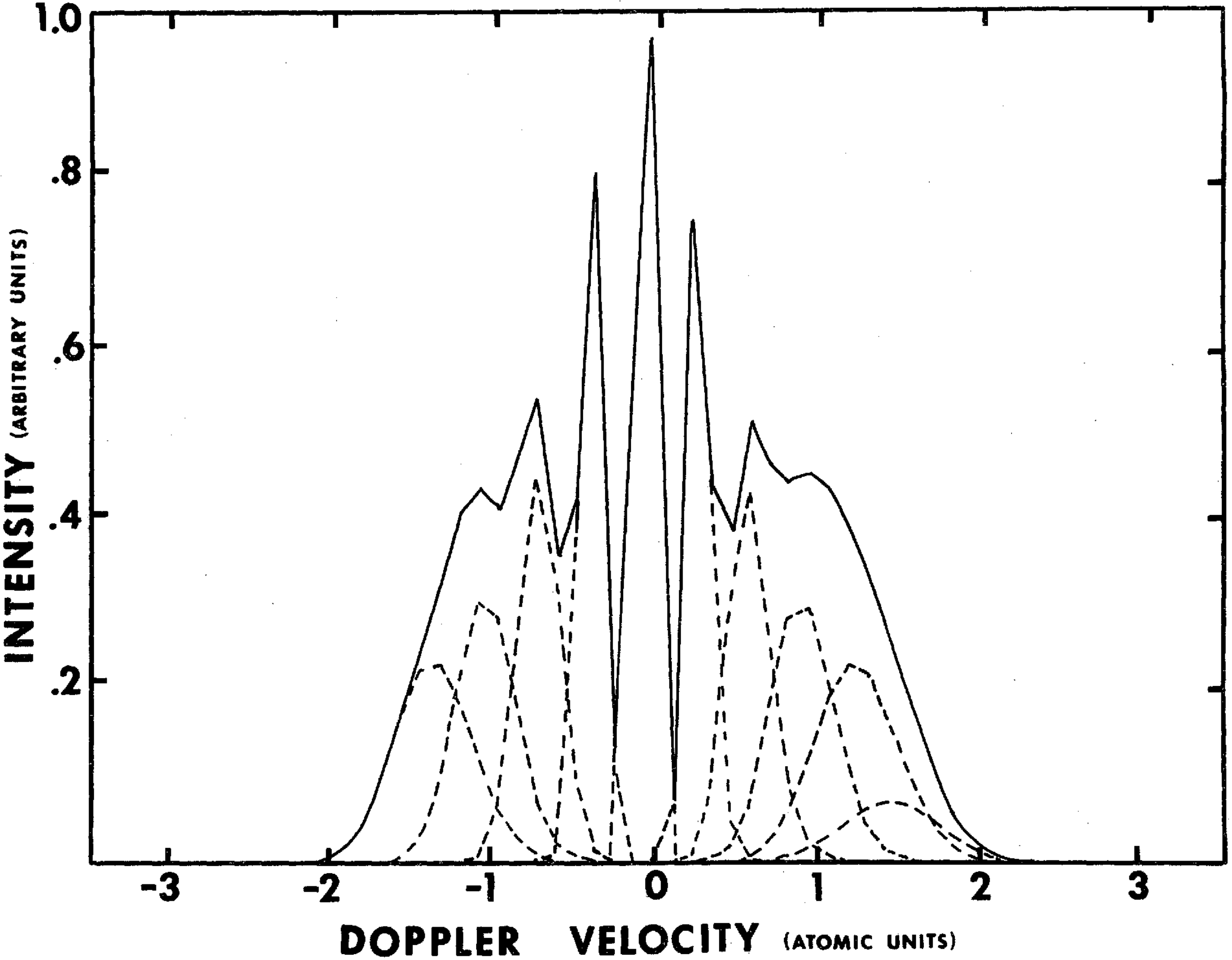
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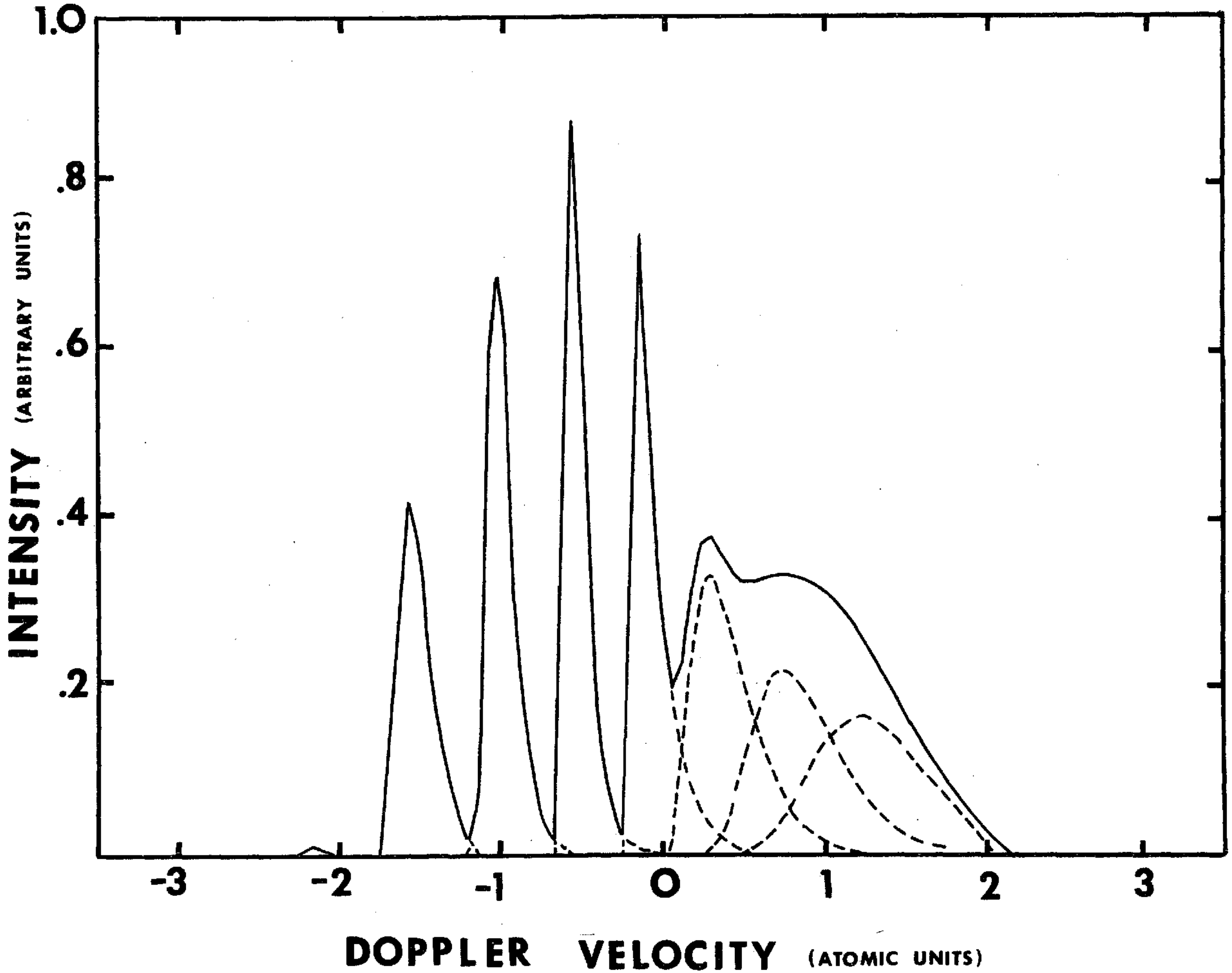
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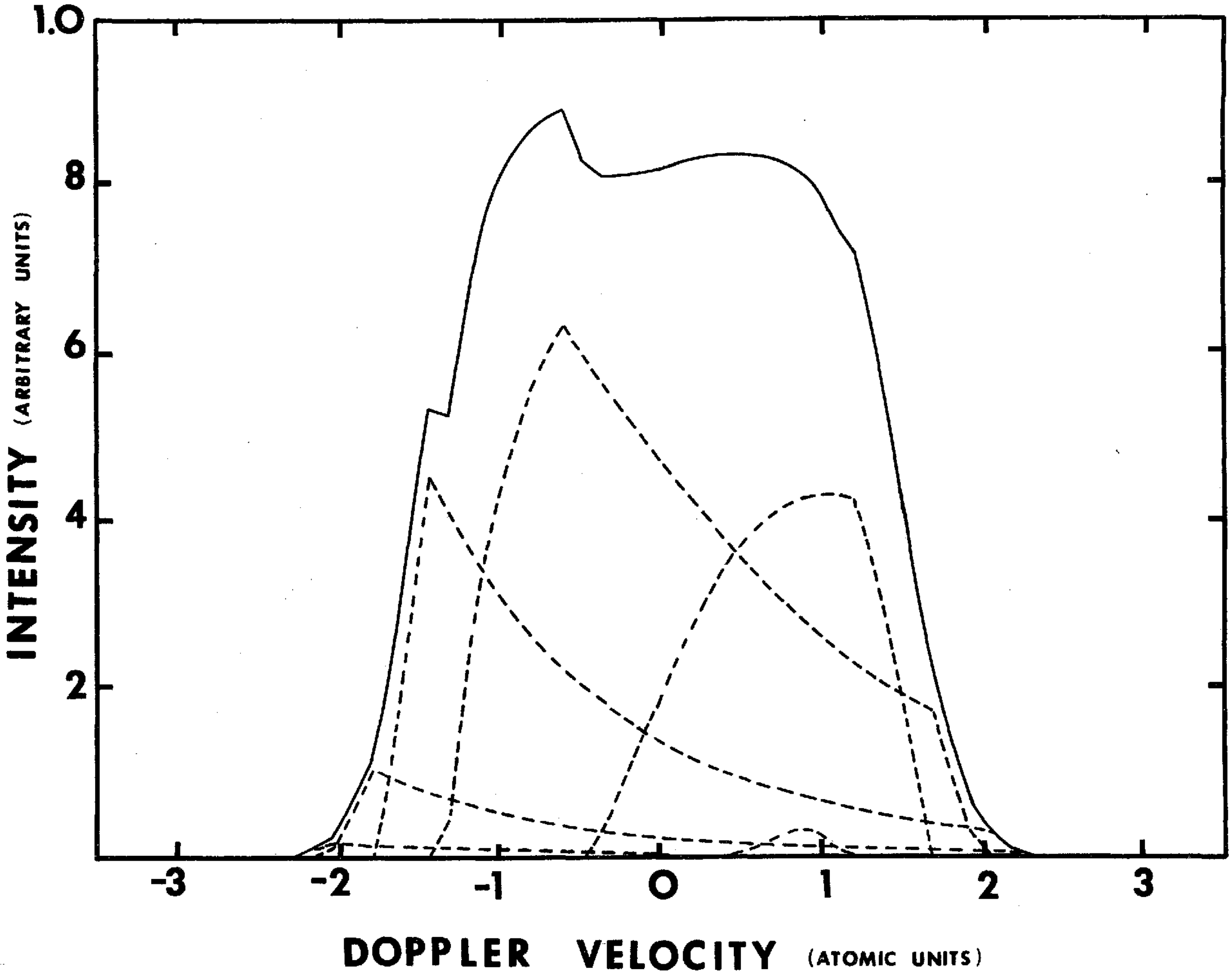

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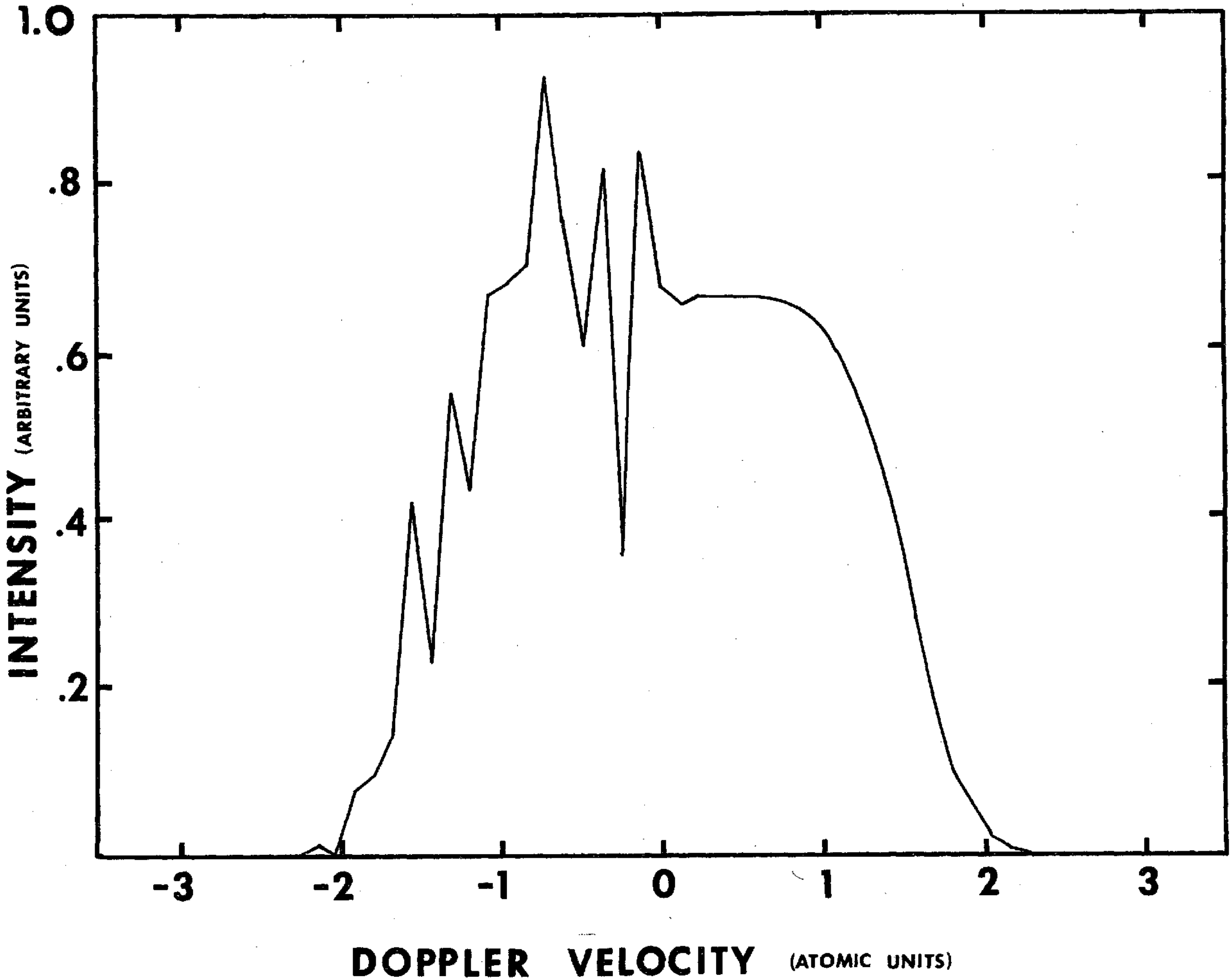

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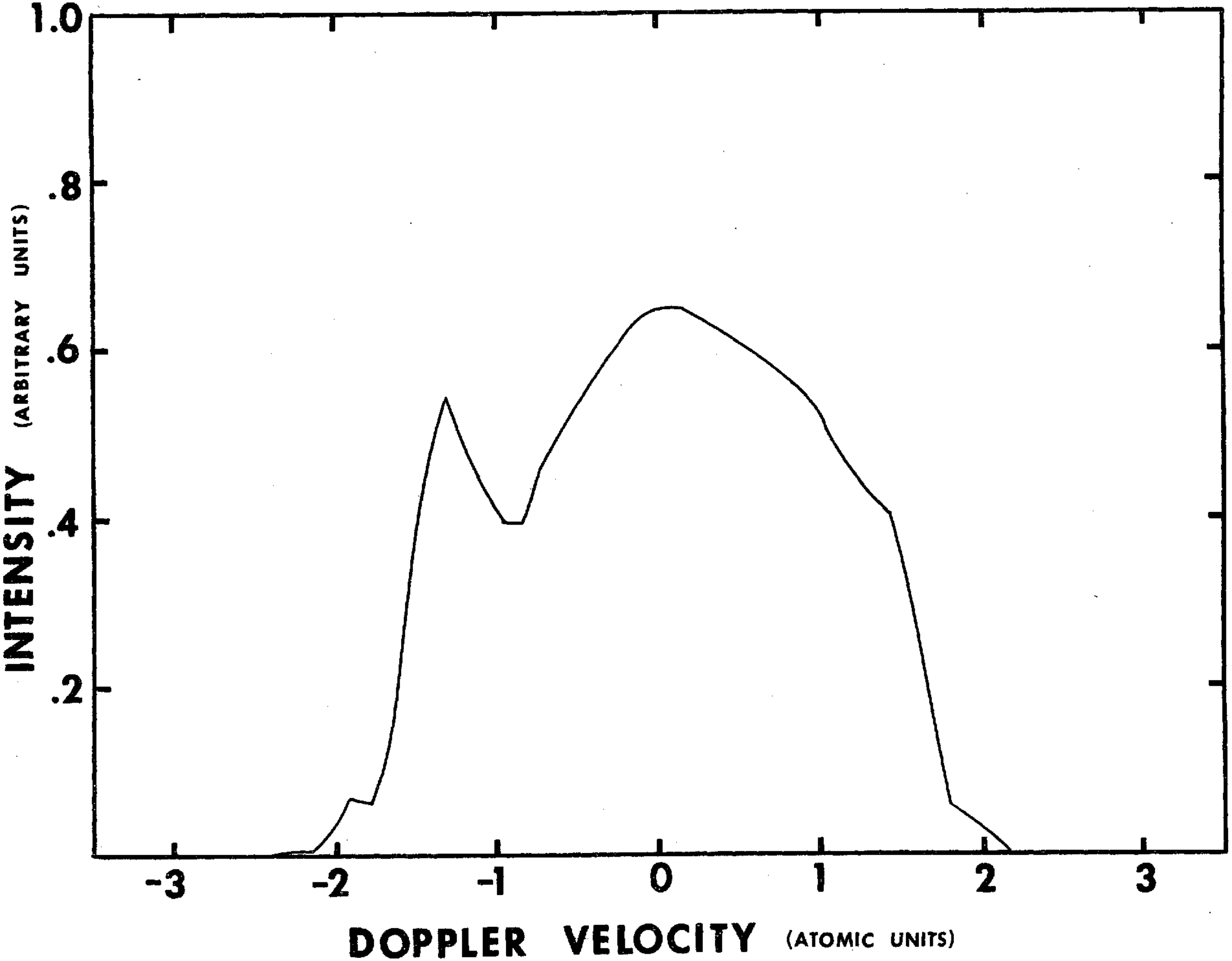
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