OBSERVATIONS OF THE J=1-0 AND J=2-1 LINES OF ^{12}CO IN L1551: EVIDENCE FOR ANISOTROPIC MASS LOSS

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Observations of the J=1-0 lines of ^{12}CO have been made to determine the extent and nature of the broad secondary velocity feature in L1551 (S239) first detected by Knapp et al. (1976). L1551 is associated with an extended Herbig-Haro object, HH102 (Strom et al. 1974), and two compact HH objects, HH28 and HH29 (Herbig 1974). Two nearby stars, HL Tau and XZ Tau, show extreme T-Tauri characteristics. The broad CO velocity component is seen toward HH102. Strom et al. (1976) have detected an infrared source near the HH objects which has a luminosity and infrared colors consistent with a late B star reddened by roughly 20 magnitudes of visual extinction (Snell 1979). The infrared source lies in the direction of the core of L1551, which has a density of 10^5 cm^{-3} (Loren et al. 1979; Snell 1979). The infrared source is likely to be embedded in this dense core.

Our observations show that the broad CO feature occurs in two locations symmetrically placed about the embedded infrared source. One region to the SW of the infrared source has broad emission at velocities lower than the narrow primary velocity component of the cloud, and the other region to the NE has broad emission at higher velocities. The high and low velocity features are at roughly 11.5 km s^{-1} and 1.2 km s^{-1}, shifted by ±5 km s^{-1} from the narrow cloud-emission at 7 km s^{-1}. The total velocity extent of the broad components is 25 km s^{-1}.

Observations of J=2-1 ^{12}CO show broad emission features that are enhanced over the J=1-0 emission in many of the positions to the SW, suggesting that the broad CO emission comes from warm, optically thin material. The low optical depth is substantiated by the non-detection of J=1-0 ^{13}CO emission at the velocity of the broad component. The excitation temperature of the narrow CO component is T_{ex}=10-15K, but from the ratio of the J=2-1 to J=1-0 emission the broad CO component to the SW has T_{ex}>25K in some regions.

The broad CO emission likely has a common origin with the HH objects. It has been suggested that the HH emission arises from shocked regions generated by mass loss from young, luminous stars embedded in

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the clouds (Schwartz 1978; Dopita 1978; and Raymond 1978). The radial velocities of HH102 and HH29 have been measured by Strom et al. (1974) and these objects are moving toward the observer at much higher velocities than the CO from which the broad lines come. Recently the proper motions of HH28 and HH29 were measured (Cudworth and Herbig 1979). These are directed away from the infrared source with velocities around 140 km s^{-1}. The broad CO emission is likely produced by material moving away from the infrared source with velocities of roughly 5 km s^{-1} directed in two streams, one to the NE and away from the observer, and one to the SW and toward the observer. Shock heating produces the higher excitation temperatures observed in the broad CO features. HH28 and HH29 move with the SW stream but at much higher velocities. The optical emission is seen only in the SW stream because it is directed toward the front face of the cloud.

The high velocities of HH28 and HH29 fit in well with the model of Norman and Silk (1979). The HH objects are ejected at high velocities by the interaction of mass loss from a young, luminous object and the infall of cloud material. The broad CO features may be the result of an interaction between the ejected material and the ambient cloud. The total mass of gas of the broad components is 0.05 $M_\odot$ in the NE feature and 0.10 $M_\odot$ in the SW feature. The total kinetic energy in the broad components is 3×10^{43} ergs. A rough time scale for mass-loss activity can be estimated from the expansion time for HH28 and HH29, assuming they have been moving at a constant velocity. This time scale is around 1000 years. Over this period of time a mass-loss rate of 10^{-7} $M_\odot$/yr. with a wind velocity of 100 km s^{-1} is needed to produce the observed kinetic energy present in the broad features, neglecting radiative cooling losses. This is a modest mass-loss rate; many estimates of the mass-loss rate for T-Tauri stars and Herbig Ae-Be stars are as large as 10^{-5} $M_\odot$/yr. This research was supported in part by NSF Grants AST 77-28475 and AST 75-13511.

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