The normal state of conduction electrons in metals at low temperatures has been described in terms of the standard theory of a Fermi liquid introduced soon after the advent of quantum mechanics and completed by Landau and others by the middle of the 20th century (1). Fermi liquid theory describes the nature of a quantum liquid of interacting itinerant fermions below a characteristic temperature $T_{FL}$, which can be far below the bare Fermi temperature $T_F$. The state above $T_{FL}$ but below $T_N$ is itself a correlated quantum liquid that can extend down to very low temperatures close to a quantum critical point (Fig. 1A) (2).

Yang and Pines (3) and Shirer et al. (4) present a phenomenological description of such a correlated quantum liquid known as the Kondo liquid (5). In the simplest case of the Anderson lattice model, a Kondo liquid arises in a system of electrons in a conduction band hybridized with a half-filled and narrow f-band. The effect of the Coulomb interaction is to suppress double occupancy of the f-orbital on each atomic site, leading to Mott localization in the absence of hybridization. The effect of hybridization is to dope the f-band with holes in a way reminiscent of hole doping of a narrow d-band in the copper oxide superconductors via the effects of chemical substitution or pressure (e.g., 5, 6).

The Yang and Pines model (3) of the Kondo liquid has a particularly simple form at the quantum critical point separating the magnetic and nonmagnetic state where $T_{FL}$ vanishes (Fig. 1A). In the low temperature limit, the Kondo liquid state is defined by an entropy $S$ and magnetic susceptibility $\chi$ of the following form:

$$S \sim T_K \sim T \ln(\theta / T)$$  \hspace{1cm} [1]$$

where $0$ is a scale that is defined here later. This differs from the Fermi liquid form expected for $T < T_{FL}$ by the logarithmic correction factor $\ln(\theta / T)$, which is characteristic of a marginal Fermi liquid state (7–11). If $S/T$ is considered a measure of the mass of fermionic quasiparticle excitations, the Kondo liquid can be viewed as a state with singular mass renormalization in the limit $T \rightarrow 0$ K.

Yang and Pines (3) go beyond this marginal Fermi liquid limit by introducing a two-fluid model to extend the description of the Kondo liquid away from the quantum critical point and up to a temperature scale $T^*$ above which hybridization between the conduction and f-electron states becomes ineffective. In practice, $T^*$ is defined as the temperature at which the entropy reaches $R \ln 2$ per mole of f states, which is less than the relevant crystal-field energy splitting.

In the two-fluid model, one fluid represents “heavy fermion carriers” of fraction $f_h(T)$ and the other fluid represents “local moments” of fraction $f_l(T)$ and the other fluid represents “local moments” of fraction $f_l(T)$. The heavy fermion fraction vanishes below $T_N$ (Fig. 1A). For $f_h > 1$, the local moment fraction vanishes and the heavy carrier fraction reaches unity at a finite temperature $T_h$.

Below a still lower temperature $T_{FL}$ (Fig. 1A), the system condenses into a Fermi liquid state characterized by fermion quasiparticles of strongly enhanced but nonsingular masses excited about a Fermi surface importantly enclosing hybridized f-electron and conduction electron states (e.g., 12). For $f_h < 1$, on the contrary, the local moment fraction fails to vanish at any temperature. Local moments then coexist with heavy carriers that mediate a magnetic interaction analogous to the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction (5). This interaction leads to antiferromagnetic order at finite temperatures (below the Néel temperature, $T_N$, in Fig. 1A). Close to and above $T_N$, the local moment fraction deviates from the above model as a result of “relocalization,” i.e., a precursor to magnetic order.

Thus, the two-fluid model describes the Kondo liquid essentially in terms of two universal exponents, namely a three-halves exponent defining the temperature dependence of the heavy carrier fraction $f_h(T)$, and a marginally sublinear exponent defining the temperature dependence of the heavy carrier entropy and susceptibility times temperature. The corresponding contribution of local moments involves no new universal functions and is given by $(1 - f_h(T))$ times $R \ln 2$ for the molar entropy and $(1 - f_h(T))$ times the Curie constant for the susceptibility times temperature.

This remarkably simple two-fluid description has been used to correlate a large
These have led to local and nonlocal hybridization interactions associated with spin, gauge, or at low temperatures has arisen in models sublinear form of the heavy carrier entropy descriptions. In particular, the marginally is also consistent with some microscopic 4f and 5f systems.

The phenomenological two-fluid model is also consistent with some microscopic descriptions. In particular, the marginally sublinear form of the heavy carrier entropy at low temperatures has arisen in models including effects of singular fermion interactions associated with spin, gauge, or hybridization field fluctuations (7–11). These have led to local and nonlocal marginal Fermi liquid descriptions, the temperature in the two-fluid model, i.e., ln(θ / T)(1 – T / T*)^3/2, with 0 equal to eT*, has been found to follow closely that predicted by dynamical mean field theory (13, 14).

The quantities f_0(T) and f_1(T) are, at first sight, analogous to the normalized superfluid and normal densities, respectively, in the two-fluid model of liquid He II (15). In contrast to the latter, however, there is no change in symmetry and no well-defined transition at T*.

The two-fluid model of Yang and Pines and Shirer et al. provides a simple operational way of thinking about a complex cooperative state of matter.