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Demixing of Aqueous Polymer Two-Phase Systems in Low Gravity*

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Abstract

When polymers such as dextran and poly(ethylene glycol) are mixed in aqueous solution, biphasic systems often form. On Earth the emulsion formed by mixing the phases rapidly demixes because of phase density differences. Biological materials can be purified by selective partitioning between the phases. In the case of cells and other particulates the efficiency of these separations appears to be compromised by the demixing process. To modify this process and to evaluate the potential of two-phase partitioning in space, experiments on the effects of gravity on phase emulsion demixing were undertaken. The behavior of phase systems possessing phase density differences and systems with essentially identical phase densities was studied at one-*g* and during low-*g* parabolic aircraft maneuvers. Results indicate that demixing can occur rather rapidly in space, although more slowly than on Earth. We have examined the demixing process from a theoretical standpoint by applying the theory of Ostwald ripening. This theory predicts demixing rates many orders of magnitude lower than observed. Other possible demixing mechanisms are considered.

INTRODUCTION

When pairs of polymers are dissolved in water, two immiscible liquid phases often form. A common pair is the poly(glucose) dextran and poly(ethylene glycol) (PEG), which form a PEG-rich phase floating on top of a dextran-rich phase, both phases containing primarily water (approximately 90% w/w). On Earth, an emulsion formed by mixing the phases rapidly demixes because of differences in phase density (*1*, *2*). Biological materials can be selectively partitioned between one or both phases and the phase interface. By manipulating system composition, separations have been achieved on the basis of a variety of molecular and surface properties, including cell membrane hydrophobic properties, surface charge, and membrane antigenicity (*1–6*). Recent work on the mechanism of cell partition has shown that there is a nonthermal randomizing process present which reduces particle separation efficiency below the value predicted thermodynamically. This stochastic energy is believed to be associated with hydrodynamic interactions present during rapid emulsion demixing (see below) (*2*, *7*).

A major goal of our research is to carry out two-phase partition experiments in the low-gravity (*g*) environment of space. Low-*g* is expected to present the advantages of reduced cell sedimentation and a reduced rate of phase emulsion demixing. The stochastic interactions discussed above are expected to be markedly reduced, thus providing an opportunity to carry out unique particle purifications (*7–10*).

The aqueous-polymer phases can be mixed easily by mechanical agitation, due to the low interfacial tension between the phases [roughly

10^{-2} to 10^{-4} dyn/cm (*1*)]. The question we address in the present manuscript is what happens after mixing when gravitational effects are virtually absent. Following agitation in one-*g*, phase droplets rapidly grow to form millimeter-sized phase regions which undergo rapid, gravity induced convection (*1*, *2*, *7*, *8*). It is this latter, convective process which should be eliminated in low-*g*.

We have identified five mechanisms which can potentially contribute to demixing aqueous polymer two-phase systems in low-*g*: Ostwald ripening (*12–15*), wall wetting (*16*, *17*), nucleation, spinodal decomposition, and coalescence (*18–21*). We consider the Ostwald ripening mechanism in detail in the present manuscript. This theory has been used successfully to explain the growth of large crystals by diffusive transport of material from small crystals. Here we perform a heuristic derivation of Ostwald ripening theory and apply the resulting equations to predict the rate at which large phase droplets will grow at the expense of smaller droplets.

We have also experimentally measured the rate of one-*g* phase demixing of isopycnic biphasic systems, i.e., systems with insignificant phase density differences, and the rate of phase demixing of a nonisopycnic system during low-*g* parabolic maneuvers in NASA KC-135 aircraft.

MATERIALS AND METHODS

Two-Phase Systems

The preparation and physicochemical characterization of aqueous polymer two-phase systems have been described previously (*3–11*). Isopycnic dextran–ficoll two-phase systems were prepared following the description of their existence by Albertsson (*1*). Small amounts of PEG were added to the systems to achieve equal phase density at lower total polymer concentration. All two-phase systems were prepared by mixing appropriate weights of the following aqueous stock solutions: 30% (w/w) dextran (D) T500 ($\bar{M}_w$ = 461,700, $\bar{M}_n$ = 181,700, Pharmacia Fine Chemicals, lot 3447), 30% (w/w) DT40 ($\bar{M}_w$ = 40,000, $\bar{M}_n$ = 33,000, lot F1-18974), 30% poly(sucrose) ficoll (F) 400 ($\bar{M}_w \cong$ 400,000, lot 7867), 30% PEG 8000 ($\bar{M}_w$ = 6650 (*23*), Union Carbide, lot B529-9014), 0.60 *M* sodium chloride, 0.24 *M* sodium phosphate buffer pH 7.5. All reagents were ACS grade or better from various sources.

Dextran concentrations were determined polarimetrically and PEG concentrations by gravimetric and refractive index measurements (*3*, *11*). Once compounded, systems were filtered (0.45 μm filter, Sybron Nalge, Inc.) and allowed to equilibrate for 24 h at experimental temperature.

Phase systems were physically characterized (Table 1) by measuring: (a) interfacial tensions, using the rotating drop method (*22*); (b) phase diagram tie-line lengths (*11*); (c) phase densities; and (d) phase viscosities (*11*, *22*, *24*). In order to obtain these measurements, isopycnic systems were altered by increasing or decreasing the PEG concentration 0.3% w/w from the isopycnic values in order to float one phase on top of the other, and values were interpolated to provide those for the isopycnic compositions. The data given in Table 1 represent the averages of at least 10 independent determinations.

Phase systems are designated, according to convention (*3*, *11*), as (*a*,*b*,*c*)*d* where *a*, *b*, and *c* refer to the % (w/w) concentration of dextran T500, PEG, and ficoll, respectively, in the system. Systems containing dextran T40 are designated with an asterisk: e.g., (*a**,*b*,*c*)*d*. Parameter *d* refers to buffer composition: I = 109 m*M* Na_2HPO_4, 35 m*M* NaH_2PO_4, pH 7.2; V = 150 m*M* NaCl, 7.3 m*M* Na_2HPO_4, 2.3 m*M* NaH_2PO_4, pH 7.2; and VI = 85 m*M* $NaHPO_4$, 25 m*M* NaH_2PO_4, pH 7.5.

In order to better visualize phase demixing, the PEG-ficoll-rich phases were dyed by including (0.05 mg/mL) trypan blue (Aldrich) in the systems. At this concentration, system physical properties were not affected.

Unit-*g* and Low-*g* Demixing Experiments

One-*g* and low-*g* demixing experiments were undertaken using an apparatus (Fig. 1) consisting of a Nikon F3 camera with Kodacolor ASA 400 film and a 55-mm, 1.28 Nikon Macrolens anchored to a platform holding a removable phase-module, backlit by a fluorescent light box. The clear Plexiglas module contained four chambers 30 mm high, 8 mm wide, and 6 mm thick (light path axis) and a digital clock. Each chamber contained a 5-mm diameter stainless steel ball to facilitate emulsification of the phases when the module was shaken manually. Usually the air-liquid interface aids in emulsification upon shaking, but in low-*g* and control demixing chambers, air spaces were eliminated.

All experiments were carried out on systems containing equal volumes of each phase. A typical low-*g* or control experiment involved mixing the phases by inverting the module 30 times, starting the timer, localizing the module on the experimental platform, and taking 10 pictures at 1- to 2-s intervals (Figs. 1–4).

TABLE 1
Composition and Physical Properties of Phase Systems

Composition[a] (% w/w) (D, PEG, F)		Phase viscosity (cP)		Phase diagram tie line length (% w/w)	Interfacial tension (µN/m)	Phase density (g/mL)	
		PEG-F-rich	D-rich			PEG-F	Dextran
(7*,5,0)	V	5.0	12.2	11.69	6.0	1.027	1.058
(5.5,0.7,9.5) Isopycnic	VI	19.4	39.6	ND	3.9	1.072	1.072

[a] Equal volumes of each phase, containing the polymers dextran (D) T500 or *dextran T40, PEG 8000, and ficoll (F) 400, and the buffer salts noted in the Materials and Methods Section. Buffer VI contains sodium phosphate while V is phosphate-buffered saline. ND = not determined.

FIG. 1. KC-135 low-*g* phase demixing experiment.

Low gravity experiments were performed aboard NASA KC-135 aircraft. The aircraft flew a series of parabolas in which the experiments and personnel on board experienced up to 30 s of low-*g* (Fig. 1) (*8*, *25*). The acceleration experienced by the partition module was monitored by three accelerometers (Sundstrad Data Controls, Model 300A1) mounted to the experimental platform on orthogonal axes, one of which was parallel to the sample vertical axis and two of which were parallel to the aircraft's major axes. For a typical maneuver the low-*g* acceleration on all axes averaged less than $10^{-2}\,g$.

Demixing experiments on isopycnic systems at one-*g* (Figs. 2 and 3) were conducted under conditions similar to those described above using Plexiglas chambers 50 mm high, 10 mm wide, and 10, 7.5, 5, or 2.5 mm thick. Mixing was accomplished by manually stirring the phase system with a plastic rod.

To quantify the demixing rates, slides prepared from negatives were projected onto paper, the outlines of connected domains traced, and the area of each domain estimated using an IBM-PC computer equipped with a Microsoft Mouse mechanically fixed to a single orientation. A

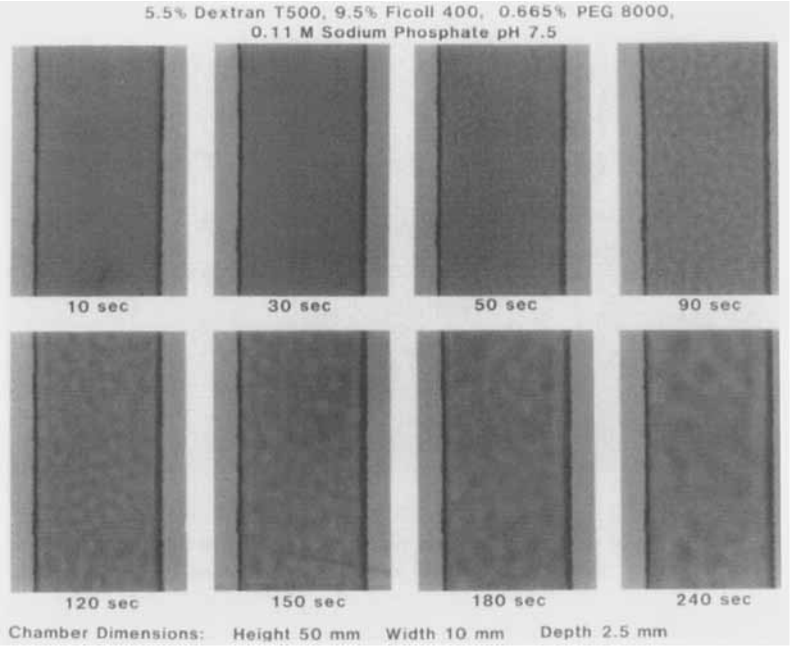

FIG. 2. Droplet growth with time in a (5.5,0.7,9.5) VI isopycnic system containing 0.05 mg/mL trypan blue dye. Chamber dimensions: 50 × 10 × 2.5 mm.

program was developed which used the screen cursor movement, created by tracing the domain outlines with the Mouse, to digitize and store the pictures of the areas as polygons. The domain area was calculated by adding the areas of the trapezoids formed from the individual sides of the polygon and the projection of each side onto the horizontal axis.

An example of the result of each stage is shown in Fig. 5 where a distribution of the drop areas measured is also illustrated. The mean and standard deviation of each histogram was calculated, the radius of a circle of area equal to the mean area determined, and the results expressed as a function of time on a log-log plot. These plots were then subjected to linear regression analysis (Table 2); the line of best fit is illustrated in Fig. 6.

Coatings and Contact Angle Measurements

The effect of alteration in partition chamber materials on phase wetting behavior was briefly evaluated by contact angle measurements

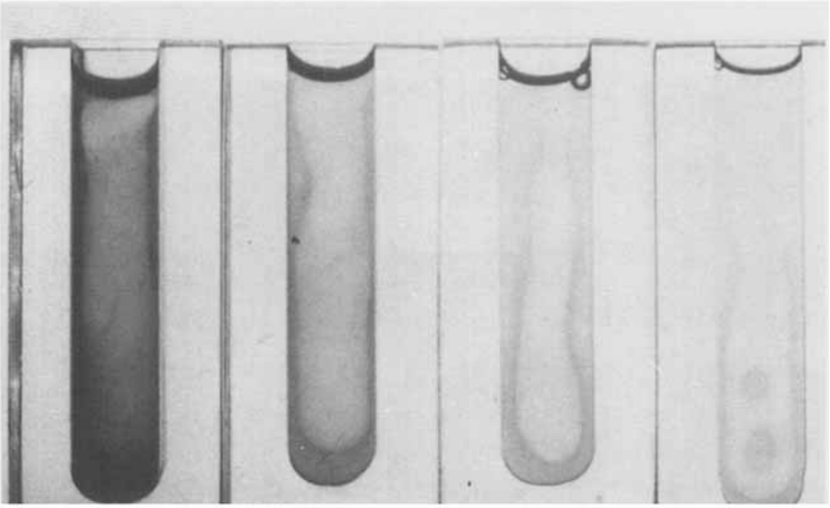

FIG. 3. Appearance of demixed isopycnic phase system 10 min after mixing. Chamber dimensions: 50 × 10 × 10, 7.5, 5, or 2.5 mm.

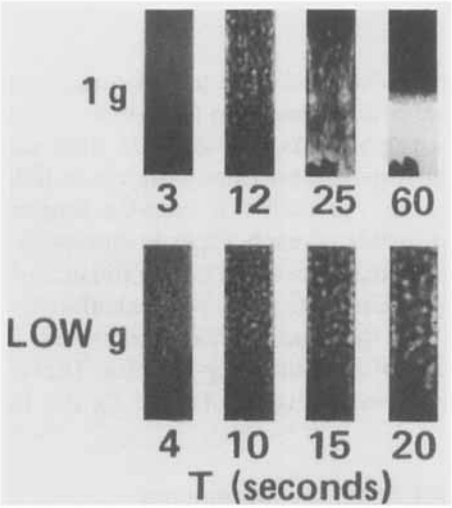

FIG. 4. Unit-*g* and low-*g* demixing of (7*,5,0) V two-phase system containing 0.05 mg/mL trypan blue dye.

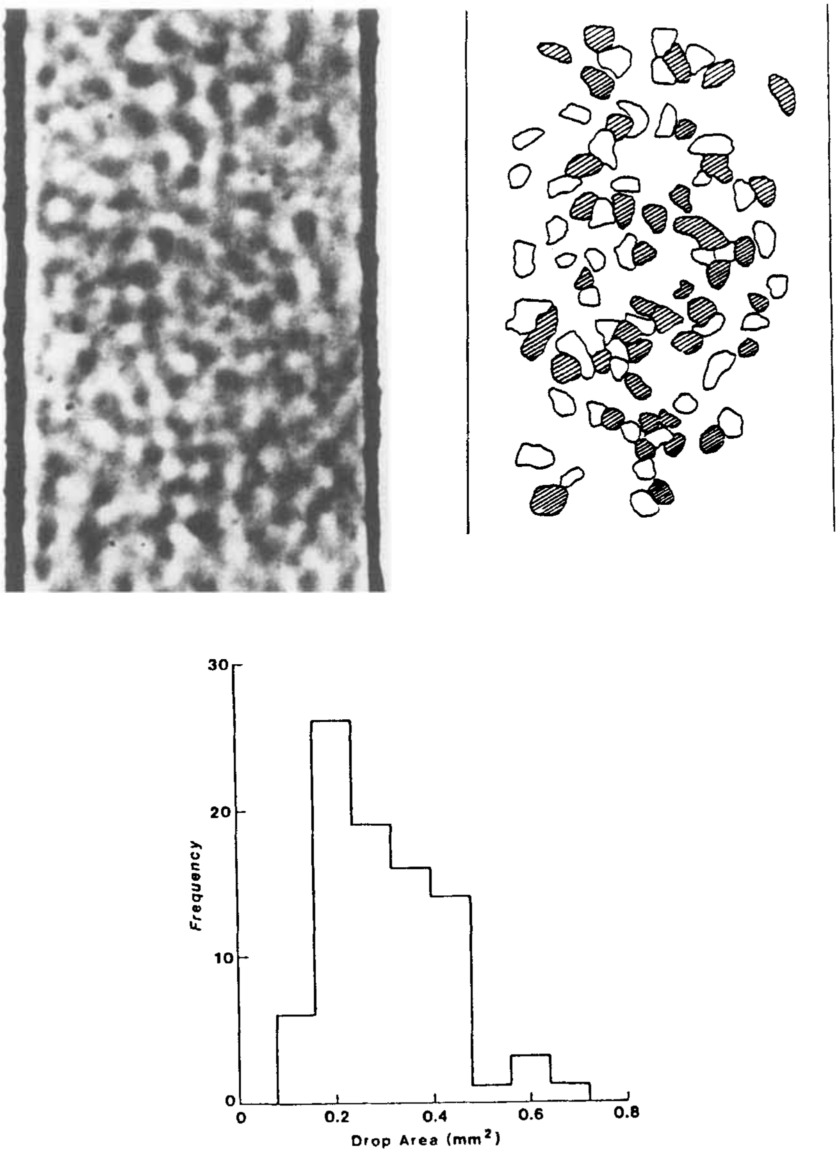

FIG. 5. Quantitation of demixing in isopycnic system in Fig. 3. Upper left: Detail 90 s after mixing. Upper right: Tracing of dyed and undyed areas. Bottom: Distribution of traced areas.

TABLE 2
Regression Parameters of Phase System Demixing Kinetics

System[a]		Power law parameters[b] *A*	*B*	*r*
Isopycnic: 1 g				
(5.5,0.7,9.5)	VI	−2.11	0.80	0.985
(7,0.3,12)	VI	−1.23	0.55	0.970
KC-135: ⩽0.01 g				
(7*,5,0)	II	−1.22	0.78	0.954

[a] Equal volumes of each phase. Phase system composition as noted in Table 1 and in the Materials and Methods Section.

[b] Log (radius; mm) = $A + B \log (t;\ s)$; r = correlation coefficient.

(*2, 26*) after the method of Schürch et al. (*27*). This involved measuring the angle of contact between a 5-μL droplet of the denser dextran-rich phase resting on an appropriate glass or Plexiglas [poly(methyl methacrylate)] slide immersed in the PEG–ficoll-rich phase. Contact angles of 0, 90, and 180° represent, respectively, complete wetting of the slide by the dextran-rich phase, equal wetting by both phases, and complete wetting by the suspending phase.

Theory: Ostwald Ripening

When two immiscible liquids of different density are emulsified, a mixture of droplets forms. In the presence of a gravitational field, these droplets will agglomerate by sedimentation and the emulsion will demix. If, however, the two liquids are of identical density, or if there is no sensible gravitational field acting, sedimentation plays no role. Rather, the two emulsified liquid phases might be expected to demix in order to minimize the surface area of contact between them and to preferentially localize one phase next to the container wall (*16*). In the following discussion we treat the dynamics of this separation process as an example of Ostwald ripening. This concept has been successfully used to explain how large crystals grow at the expense of small crystals (*15*). We have derived the equations required to apply this same concept to the transport of materials from microscopic regions to large droplets of one polymer-enriched phase suspended in the other.

Consider a chemical substance A, which is partitioned between a submicroscopic droplet of radius *R* and an exterior phase. The con-

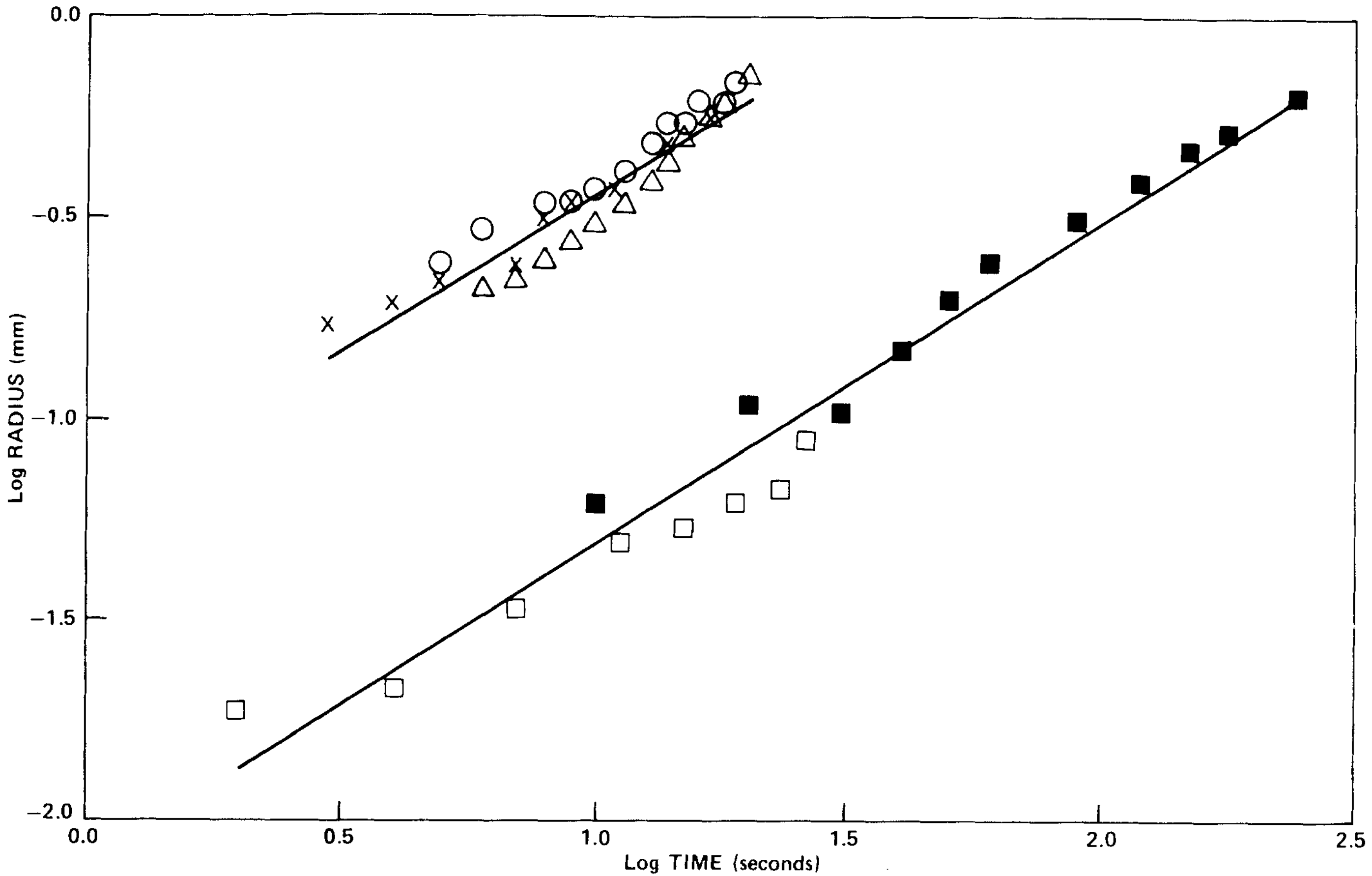

FIG. 6. Plot of log time after shaking versus log radius (based on equivalent domain diameter) for (7*,5,0) V system at low-*g* (○, △, ×) and isopycnic (5.5,0.7,9.5) VI system at unit-*g* (□, ■). Symbols represent individual experiments.

centration of A just outside the droplet is $C_A(R)$. In the limit that the two phases are separated by a flat surface (infinite radius of curvature), the equilibrium concentration is $C_A(\infty)$. The two concentrations are related by the Gibbs-Kelvin equation:

$$C_A(R) = C_A(\infty) \exp (2\sigma v_A/RkT) \qquad (1)$$

where σ is the interfacial tension between the phases, v_A is the molecular volume of A, k is Boltzmann's constant, and T is the absolute temperature. $C_A(\infty)$ is the thermodynamic concentration of A in the exterior phase given by the appropriate phase diagram. Equation (1) shows that the concentration of A in the exterior phase outside a droplet of radius R is always greater than $C_A(\infty)$.

When two phases, initially having a flat surface of contact between them, are shaken, droplets with a distribution of sizes form. Immediately after mixing, $C_A(R) = C_A(\infty)$ for all $R < \infty$, but as shown in Eq. (1), at equilibrium $C_A(R) > C_A(\infty)$ for all $R < \infty$, so A will diffuse from the droplets to the exterior phase. That is to say, these regions begin to shrink. This causes the concentration of A in the exterior phase to rise. At some point in time, the concentration of A reaches the value $C_A(R_n)$ which is the concentration of A in equilibrium with a droplet of radius R_n, where R_m is the radius of the largest droplet in the distribution and R_n represents a distribution of smaller droplets. When the concentration of A in the exterior phase around the small droplet of radius R_n exceeds $C_A(R_m)$, the largest droplet begins to grow by accretion of A. Droplets of radii smaller than R_m continue to shrink. As the time t approaches ∞, droplets with radii smaller than R_m disappear, leaving behind the largest region or droplet, whose radius has grown to the point that it approaches equilibrium with the flat surface concentration $C_A(\infty)$.

The rate at which the droplet of maximum radius, R_m, grows depends upon the rate at which A enters this droplet. We assume that this rate is governed by the rate at which A diffuses from the bulk of the solution to the surface of the droplet. This can be expressed in terms of an effective rate constant, $k = 4\pi D_A R_m$, where D_A is the diffusion coefficient for transport of A through the exterior phase (*33–35*).

Starting from these considerations, a rigorous theory of the evolution rate of droplet distribution can be worked out. The mathematical development required tends, however, to obscure the physical phenomena which the theory means to describe. To avoid this, we present here a heuristic derivation of the time dependence of R_m. Although dimensionally correct, the theory ignores dimensionless constants which fortunately turn out, in the final result, to be of order unity.

As pointed out, the concentration $C_A(R_m)$ of the largest droplet proceeds asymptotically toward $C_A(\infty)$ as time advances. The concentration difference, $C_A(R_n) - C_A(R_m)$, drives the diffusion of A into the droplet. The rate of incorporation of A is $k[C_A(R_m) - C_A(\infty)] \cong D_A R_m [C_A(R_m) - C_A(\infty)]$, where we ignore the factor 4π.

It is now useful to introduce the additional complication that both the exterior phase and the droplet phase contain a second chemical component B. This may be a minor component or the major component, which acts as the solvent (see below). In any case, we assume that the rate of incorporation of B into the droplet phase is much more rapid than the rate of incorporation of A. This may be because the concentration of B is so much higher or because the diffusion coefficient of B is much greater than that of A. In either case, the physical result is that when a molecule of A reaches the surface of the droplet by diffusion through the exterior phase, there is already present at the surface enough B so as to maintain the correct equilibrium composition of the droplet upon incorporation of an additional molecule of A. If the mole fractions of A and B in the droplet are x_A and x_B, respectively, then upon incorporation of x_A moles of A, x_B moles of B are also incorporated. If the molecular volumes are v_A and v_B, respectively, the average molecular volume in the droplet is $\bar{V}$ where $\bar{V} = x_A v_A + x_B v_B$. The volume of the droplet is proportional to R_m^3 so that the number of molecules in the droplet is $R_m^3/\bar{V}$. If the rate of incorporation of molecules into the droplet by diffusion is $D_A R_m [C_A(R_m) - C_A(\infty)]$, then the rate growth of the number of molecules in the droplet is given by

$$(1/\bar{V})(dR_m^3/dt) \cong D_A R_m [C_A(R_m) - C_A(\infty)] \tag{2}$$

which is an equation of motion for R_m taken as a function of time. To integrate Eq. (2) we first evaluate Eq. (1) at $R = R_m$ and expand the exponential for the case $(2\sigma v_A/R_m kT) \ll 1$. The result is

$$C_A(R_m) = C_A(\infty)(1 + 2\sigma v_A/R_m kT) \tag{3}$$

Ignoring the factor of 2 in Eq. (3), we substitute this result into the right-hand side of Eq. (2) to obtain

$$(1/\bar{V})(dR_m^3 dt) \cong D_A R_m [C_A(\infty)(1 + \sigma v_A/R_m kT) - C_A(\infty)] \tag{4}$$

By canceling common factors, this equation can be rewritten

$$dR_m^3/dt \cong D_A C_A(\infty)\sigma \bar{V} v_A/kT \tag{5}$$

Since $R_m(t)$ at large t is much larger than $R_m(0)$, we may take $R_m(0) = 0$ and integrate Eq. (5) directly to obtain

$$R_m^3(t) \cong D_A C_A(\infty)\sigma \bar{V} v_A/kT \cdot t \tag{6}$$

which shows that $R_m^3(t)$ increases linearly with time t.

In the rigorous derivation which this derivation replaces, $R_m(t)$ is replaced by $R(t)$, the radius of the average droplet in the distribution. The maximum radius, $R_m(t)$, is just 50% larger, a difference which is unimportant in a heuristic derivation. Also, in the rigorous derivation, the right-hand side of Eq. (6) appears multiplied by a factor of 8/9, which is again of the order of unity (*15*).

Our results may be summarized by saying that as the small phase regions dissolve, we are left with a single droplet. According to Eq. (6), the radius, $R_m(t)$, of this droplet grows asymptotically with time as $t^{1/3}$, while the volume of the droplet grows linearly with t.

We can apply Eq. (6) to the specific case of demixing in an aqueous-polymer phase system, identifying dextran as Compound A and PEG as Compound B. Dextran of $\overline{M}_n$ 185,000 has a molar volume of 0.611 cm^3/g (*2*), hence its molecular volume can be calculated to be 1.88×10^{-19} cm^3/molecule. Similarly, PEG of $\overline{M}_n$ 6650 has a molar volume of 0.833 cm^3/g (*2*) and a molecular volume of 9.20×10^{-21} cm^3/molecule. We have chosen a typical phase system (*1*) in which the composition of the exterior phase is 1.05% dextran (mole fraction $x_{\text{dex}} = 1.13 \times 10^{-6}$), 5.7% PEG ($x_{\text{PEG}} = 1.65 \times 10^{-4}$), and 93.25% water ($x = 1$, $\bar{V} = 2.99 \times 10^{-23}$ cm^3/g). The average molecular volume in the droplet, $\bar{V}$, is calculated to be 3.16×10^{-23} cm^3. For this system we have measured σ as 0.02 erg/cm^2. D (dex) = $D_A = 2 \times 10^{-7}$ cm^2/s. The concentration of dextran in the exterior phase, $C_A(\infty)$, is given by $X_A/\bar{V} = 3.58 \times 10^{16}$ molecules/cm^3.

Inserting these parameters into Eq. (6) gives

$$R_m^3(t) = (2 \times 10^{-20}\ \text{cm}^3/\text{s})t \tag{7}$$

Applying this equation, we calculate that 10 weeks will be required to grow a droplet 1 μm in diameter (starting at zero). For a droplet to grow to 10 μm is calculated to take 200 years.

In conclusion, if Ostwald ripening is to provide the dominant mechanism by which the two aqueous-polymer phases demix in the absence of density differences, this demixing can be expected to take years.

RESULTS

Low-Gravity and Unit-Gravity Demixing of Normal and Isopycnic Polymer Two-Phase Systems

Initial studies of phase demixing in the absence of appreciable sedimentation were performed using isopycnic dextran/ficoll systems in which sufficient poly(ethylene glycol) (PEG) was included to equalize the density of the two phases (Table 1). These systems are rather viscous and not generally useful for cell separations but did prove to model the behavior of polymer biphasic systems in low-*g* accurately. Ten minutes after mechanical mixing at constant temperature (20°C), phase demixing was well developed in these systems (Figs. 2 and 3). Microscopically, domains enriched in one phase could be readily distinguished in a few seconds. As these regions grew and reduced interfacial area, three-dimensional bicontinuous structures formed which eventually evolved into a dextran-rich phase surrounded by the trypan-blue dyed PEG-ficoll-rich phase (*1*). This behavior was in agreement with contact angle measurements which indicated that the ficoll-rich phase would preferentially wet both glass and Plexiglas container walls (data not shown). The effects of container wetting were also seen when the thickness of the chamber containing the isopycnic system was varied (Fig. 3). As the chamber area to volume ratio increased, so did the rate of demixing, presumably due to the walls localizing a larger fraction of the PEG/ficoll-rich phase.

The behavior of (7*,5,0) V systems at low-*g* and unit gravity are shown in Fig. 4. The trypan blue dye partitions more than 90% into the PEG–ficoll-rich phase in this system. Within 3 s following mixing at unit gravity, the emulsion demixes into dispersed visible domains of each phase. By 12 s, sedimentation begins and convective streams are present by 20 s. This streaming occurs for approximately 15 s, during which time clear regions of each phase appear at the top and bottom of the chamber. As demixing progresses, the middle emulsion region slowly contracts to form a planar interface. In keeping with sedimentation being the dominant demixing mechanism, shortening chamber height decreased the time required for demixing, while decreasing chamber thickness exhibited no effect (data not shown). Undyed and trypan-blue dyed systems exhibited identical behavior. In all cases, demixing at low-*g* mimicked the behavior of isopycnic systems at unit gravity, even to the extent of early preferential localization of PEG–ficoll-rich phase at the container walls. Also, demixing of the isopycnic systems was unchanged at unit-*g* and low-*g*.

Figures 5 and 6 and Table 2 give the quantitative results obtained by the analysis process described in the Materials and Methods Section. Note that phase streaming prevents use of this procedure in analyzing the demixing of nonisopycnic systems in unit-*g*. The data for the isopycnic systems are linear on a log-log plot, implying a power law relationship between domain area and time. The log-log plot was less obviously linear in the case of the (7*,5,0) V system. Presumably, this reflects the limited time scope of the KC-135 experiments.

DISCUSSION

The preceding experiments show that aqueous polymer two-phase systems, which are characterized by moderately high viscosities and low interfacial tensions, will demix, following mixing by agitation, in the absence of appreciable gravitational influences. The mechanisms by which this demixing occurs are not known. Calculations based on our approximate treatment of Ostwald ripening strongly suggest that it is not of importance in the present case. Not only does the estimate of the time required to produce a 10-μm domain widely differ from that observed, but measured power law coefficients (Table 2) differ significantly from the $t^{1/3}$ dependence predicted. It does not seem likely that either nucleation or spinodal decomposition is involved, since the mixing/demixing process takes place at constant temperature and, presumably, constant phase composition. Since we have no evidence that the mixing process perturbs the composition of the phases from their equilibrium values, we will not consider these phase separation mechanisms as relevant.

Coalescence of phase drops in the concentrated emulsions certainly occurs, and the disposition of the separated phases appears to be governed by preferential wetting of the chamber walls by the ficoll–PEG-rich phases. If coalescence does prove to be the dominant mechanism, the present data provide a basis for testing theories describing the processes involved. Evidently, in the systems examined the size scale of the emulsion increases with time according to a power law. The rather large difference in the initial drop size for the isopycnic and (7*,5,0) systems implied by the data illustrated in Fig. 6 and Table 2 are presumably associated with the degree of demixing. It would seem that the mixing ball used in the KC-135 experiments is less efficient in this regard than the presence of air bubbles.

Our results are somewhat similar to those of others investigating the structures of immiscible metal alloys and related model systems solidified under microgravity conditions (*8*, *20*, *36*, *37*). On the other hand, it is interesting to note that Lacy and Otto (*38*) reported that fluorocarbon (Krytox) oil and water mixtures formed stable (10 h) emulsions at low-*g* on board Skylab.

In summary, our results suggest that emulsions of the type studied here will demix by a different mechanism and at a slower rate in low-*g* than on Earth. The final disposition of demixed phases, and to some extent the rate of demixing, can be controlled by manipulation of chamber geometry and surface wetting behavior. Application of polymer phase systems to space bioprocessing is in progress.

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