SPECTRAL PROPERTIES OF SELECTED PLANT SPECIES AND SOME VARIATIONS ACCOMPANYING LEAF THICKNESS, PIGMENTATION, AND DEHYDRATION

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INTRODUCTION

The relationship of plants to their energy environment can be dealt with through an understanding of the mechanisms which affect the thermal balance of the organisms. Energy (heat) is carried to and from plants by radiation, conduction, convection, transpiration, and condensation. A small amount of the total energy budget is accounted for by metabolic processes. Because of the importance of radiant energy to plants, the present paper deals with some spectral properties of selected vascular plants as well as certain cryptogamic species.

Plants constantly receive fluxes of radiant energy, both shortwave direct and indirect solar radiation and longwave thermal radiation. Some of this energy is absorbed and some is scattered. The amount of radiation absorbed is the sum of all the incident fluxes on the exposed plant parts each of which has a particular absorptivity:

$$AQ_{abs} = \sum_{i=1}^{n} a_i A_i R_i$$

where n is the total number of different plant surfaces exposed, a_i is the absorptivity of the i^{th} plant surface receiving radiation; R_i is the radiation impinging on the i^{th} surface. A_i is the area of the i^{th} exposed surface. It is possible for several of the a_i's to be equal, e.g. the mean absorptivities of leaves to radiation shorter than 2.5 μ may well be the same for a single plant. A is the total surface area receiving radiation, and Q_{abs} is the total energy absorbed. Absorptivities are functions of wavelength of the radiation and the mean absorptivity of a plant leaf is given by the following:

$$\overline{a}_i = \frac{\int a_i(\lambda) R_i(\lambda) d}{\int R_i(\lambda) d}$$

where a_i (λ) is the monochromatic absorptivity of the i^{th} plant surface, and R_i (λ) is the incident monochromatic radiation. As discussed below, the mean absorptivities of plant leaves, or cryptogamic thalli, can vary considerably.

Absorption of radiant energy as a function of wavelength has long interested botanists, foresters, ecologists, etc. And the interaction of plants and radiation of the visible portion of the spectrum has been quite thoroughly studied (1, 2). Leaf morphology is significantly related to energy absorption or scattering, and chlorophyll pigments exhibit distinct action spectra (1, 3).

METHODS

All spectral measurements were done using a Beckman DK-2A Ratio-recording Spectrophotometer. Leaves were taken from the plants and immediately placed in the spectrophotometer for measurements. In the case of lichens and bryophytes, moistened thalli were used. Since the wavelength energy is held constant by slit adjustment from 2.5 μ to .35 μ, the recorded spectral curves of either reflectance or transmittance represent percentages of a constant energy value at any wavelength. Absorption of radiation at any wavelength is then the following:

$$A\lambda = 1 - (T\lambda + R\lambda)$$

where $T\lambda$ is spectral transmittance and $R\lambda$ is spectral reflectance of the plant specimen.

The plants used in this study were selected from among many species all grown under greenhouse conditions. Since the studies involved both an assessment of water loss by an energy budget approach and a measurement of spectral properties, the choice of particular species was in part based on the ease with which their energy budgets could be studied. Still, a rather broad sampling was attained and distinct and interesting differences did appear in measured spectral properties. For sunflower, *Helianthus annuus*, changes in spectral properties accompanying water loss were also determined.

RESULTS AND DISCUSSION

What may be considered spectral properties of typical leaves are shown in Fig. 1. Both cotton, *Gossypium hirsutum* (Fam. Malvaceae) and the house plant called geranium, *Pelargonium zonale* (Fam. Geraniaceae) exhibit efficient absorption in the visible portion of the spectrum below 0.7 μ. But reflectance and transmittance both increase significantly between 0.7 μ and 0.8 μ and remain between 40% and 50% to about 1.3 μ – 1.4 μ. As a result absorption in this range of wavelengths is low. The near infrared is a region of the spectrum containing much inergy (3) and by not efficiently absorbing radiation in this spectral region plants avoid a considerable additional heat load. Absorption of infrared radiation peaks farther out at 1.45 μ and 1.95 μ coinciding with strong absorption by water at these wavelengths. Beyond 2.5 μ plant leaves and cryptogam thalli are nearly black, absorbing almost 100% of the incident radiation. But the advantage of this is that plants emit radiation efficiently at the same wavelengths at which they absorb efficiently. A plant surface at 20° C emits radiation in the infrared near 10 μ.

Epiphyllum ackermannii (Fam. Cactaceae) has a broad flattened stem which contains chlorophyll and very much reduced, almost nonexistent, leaves. *Kalanchoe pinnata* (Fam. Crassulaceae), like the Epiphyllym, has a fleshy stem but also has thickened leathery leaves. Both of these species possess spectral properties somewhat different than those of either Gossypium or Pelargonium. (Fig. 2). Considerably more radiation is reflected and transmitted by both Ephiphyllum and Kalanchoe in the visible portion of the visible portion of the spectrum; and unlike either Gossypium or Pelargonium, reflectance peaks higher than transmittance at .55 μ. Additionally there is a small absorption peak between .95 μ and 1.0 μ and another at about 1.2 μ. These peaks are barely noticeable for Pelargonium and Gossypium. Contrasted with the thinner-leaved species the thicker leaves of both Epiphyllum and Kalanchoe reflect more radiation between about .75 μ and 1.3 μ than they transmit. Additionally, reflectance remains higher beyond 1.3 μ for both Epiphyllum and Kalanchoe. Gates *et al.* (3) found the same true of thick vs. thin-leaved plants they studied: *Nerium oleander* and *Raphiolepis ovata* vs. the rather thin-leaved *Populus deltoides.*

Sunflower, *Helianthus annuus,* can be considered somewhat typical with regard to its spectral characteristics (Fig. 3). Its properties are similar to both Gossypium and Pelargonium. An experiment was done using Helianthus to determine the effects of dehydration on spectral properties of the leaves (Figs. 3, 4). Because of the strong water absorption bands centered at 1.45 μ and 1.95 μ it was thought that changes in absorption of radiation at these wavelengths with evaporation of water might be a useful indicator of moisture stress in the plant leaf. As shown in Figs. 3 and 4 these absorption peaks decrease very little with a rather substantial change in moisture content. Not until the leaf is very much wilted do significant changes occur in these two absorption peaks. As water is lost from the leaf its transmittance increases while its reflectance decreases until the leaf is completely dry. Then both reflectance and transmittance increase (Table 2). Because individual leaves on a single plant often vary in their moisture contents, a comparison was made of their reflectance properties (Fig. 5). Leaf 2 is the oldest and leaf 5 is the youngest of the four measured. In comparing different-aged leaves of white oak Gates *et al.* (3) found a young leaf to exhibit reflectance properties of protochlorophyll; but all the sunflower leaves whose reflectance curves are shown in Fig. 5 exhibit peak absorptance at .67 μ, and the curves are all very much alike.

Certain plants, *Coleus blumei* var. Victoria for example, contain abundant anthocyanin pigment in the epidermis of the adaxial sides of leaves while there is no anthocyanin in the epidermis of the abaxial sides.[1] Comparing reflectance properties of both leaf surfaces (Fig. 5), there are few differences beyond the visible region where more radiation is reflected from the abaxial than the adaxial surface. This observation compares favorably with another made on *Ilex cornuta* (3).

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[1] In discussions of the form and anatomy of the leaf, it is customary to designate the leaf surface that is continuous with the surface of the part of the stem located above the leaf insertion as the upper, ventral, or adaxial side; the opposite side as the lower, dorsal, or abaxial." (4)

The spectral properties of cryptogams – lichens and bryophytes – have been little studied. Lichens and bryophytes occur in a wide range of habitats, from open sunny areas to the deepest shade of forests. In this study the spectral properties of cryptograms studied are very similar to those of vascular plants, including distinct reflectance peaks at .55 μ in species of Parmelia and Cladonia which were not reported for other cryptogams (3), (Fig. 6). *Parmelia conspersa* is a common lichen of both eastern and western United States occurring in large loose patches on rock surfaces (5). It exhibits very little spectral transmittance but its reflectance properties are similar to those of other cryptogams (Fig. 6) and vascular plants (Figs. 1, 3). *Parmelia hyperopta* (Fig. 6) reflects about 60% of the incident radiation between .80 μ and 1.3 μ, again "avoiding" the heat load of the near infrared. Cladonia, the bryophyte mat, the Dicranum spectral reflectances shown in Fig. 6 are representative of small intact mats taken from their habitats in which the plants occurred. Note that each reflects successively less radiation. Though much more data are needed before conclusions can be drawn, the preliminary results might suggest greater spectral reflectance by cryptogams growing in open, sunny habitats compared to those growing in deep shade of forests. Gates *et al.* (3) found that desert plants, which of course are exposed to a considerable energy load, reflect much more radiation at all wavelengths than do more mesophytic plants.

In their study of spectral properties of different vegetations, Scott *et al.* (6) discussed the importance of the ratio of reflected radiation in the near infrared to that in the visible. Using the respective wavelengths .80 μ and .55 μ they point out that for single leaves the usual ratio is about 3:1 while for vegetations it is about 6:1, according to their data. Table 1 contains spectral reflectance data for selected wavelengths as well as the ratios of infrared (.80 μ) to visible (.55 μ). In this study these ratios vary considerably, but are lowest for succulents, intermediate for thin-leaved plants, and very slightly higher for cryptogams.

Finally, it is of interest to note the values of mean absorptance, calculated according to the equation given above, of a few species (Table 2.). Mean reflectance, mean transmittance and total energy absorbed are also given. Note particularly that as water is evaporated from the leaf of Helianthus, the energy absorbed increases until the leaf is completely dry. In the case of the liverwort, *Reboulia hemisphaerica,* and the lichen, *Parmelia conspersa,* mean absorptance is high mainly because transmittance is low and reflectance is not unusually high.

Spectral curves, such as the ones published here, and others published elsewhere (3, 6), give a visual indication of plant-radiation coupling. Plants are closely coupled to their radiation environment throughout the visible range of wavelengths and absorption peaks occur at about .45 μ and .65 μ. Plants are essentially decoupled from the near infrared where much heat would be absorbed, and again coupled to longwave thermal radiation.

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Table 1. Percent spectral reflectances at selected wavelengths for several plant species.

	Percent Reflectance at given λ						Reflectance Ratio:
Species	.45μ	.55μ	.80μ	1.1μ	1.7μ	2.2μ	% at .80μ/% at .55 μ
Epiphyllum Pinnata	7%	26%	55%	48%	11%	5%	2.1
Kalanchoe Ackermannii	4	17	50	44	7	4	2.9
Gossypium hirsutum	4	10	45	43	27	13	4.5
Pelargonium zonale	2	8	44	43	30	15	5.2
Helianthus annuus	5	12	46	44	30	15	3.8
Parmelia conspersa	11	22	49	51	44	29	2.2
Parmelia hyperopta	8	15	56	60	35	18	3.7
Cladonia sp.	2	5	28	37	21	11	5.1
Bryophyte mat[a]	1	3	13	16	5	1	3.7
Dicranum scoparium	1	1	10	14	10	6	6.7

[a] The bryophyte mat, collected under a stand of *Liriodendron tulipifera,* consists of *Thuidium delicatulum, Cirriphyllum illecebrum and Dicranum scoparium.*

Table 2. Mean absorptance, mean reflectance, mean transmittance and total energy absorbed. The total incident energy in each case was .73 cal cm^{-2}min^{-1}.

Species	Absorptance	Mean Values of: Reflectance	Transmittance	Energy Absorbed cal cm^{-2}min^{-1}
Gossypium hirsutum	.56	.20	.24	.41
Pelargonium zonale	.58	.20	.22	.42
Reboulia hemisphaerica	.82	.16	.02	.60
Parmelia conspersa	.69	.29	.01	.50
Helianthus annuus				
Moisture = 687%	.54	.22	.24	.39
Moisture = 438%	.54	.19	.27	.39
Moisture = 288%	.55	.17	.28	.40
Moisture = 78%	.60	.14	.26	.44
Moisture = 0%	.51	.19	.30	.37

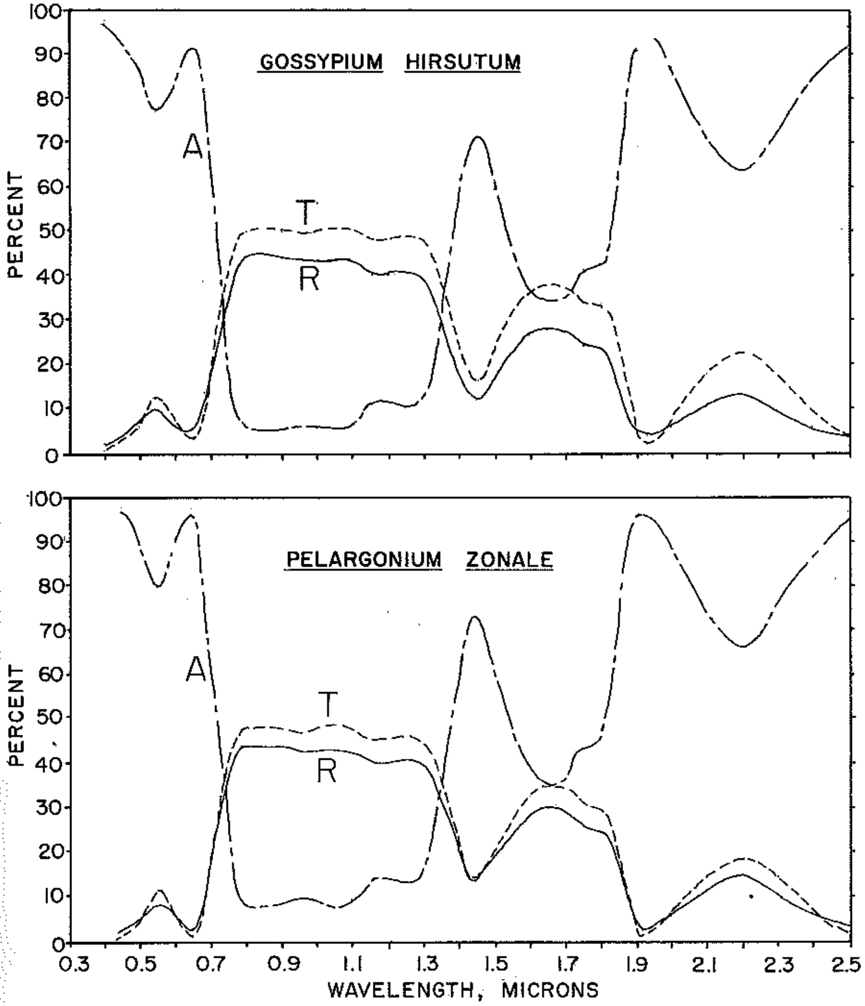

Fig. 1. Upper – Spectral reflectance (R), transmittance (T), and absorptance (A) as a function of wavelength of *Gossypium hirsutum* leaves.
Lower – The same spectral properties are given for *Pelargonium zonale*, the common household geranium. Note the similarity of the spectral curves for the two plants, both of which have moderately thin leaves.

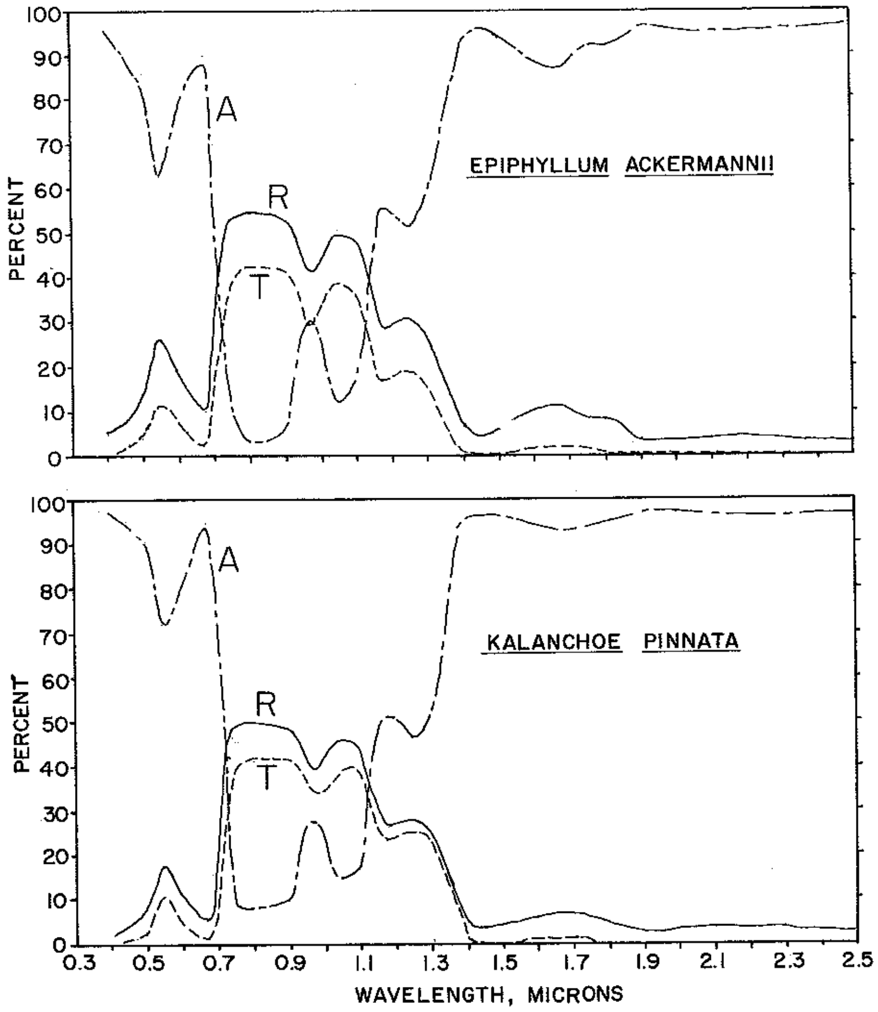

Fig. 2. Upper – Spectral reflectance (R), transmittance (T), and absorptance (A) as a function of wavelength of *Epiphyllum* ackermannii stem. Lower – The same spectral properties of *Kalanchoe pinnata*. Both these plants have thickened organs and present some interesting comparisons with leaves of "typical" plants of Fig. 1.

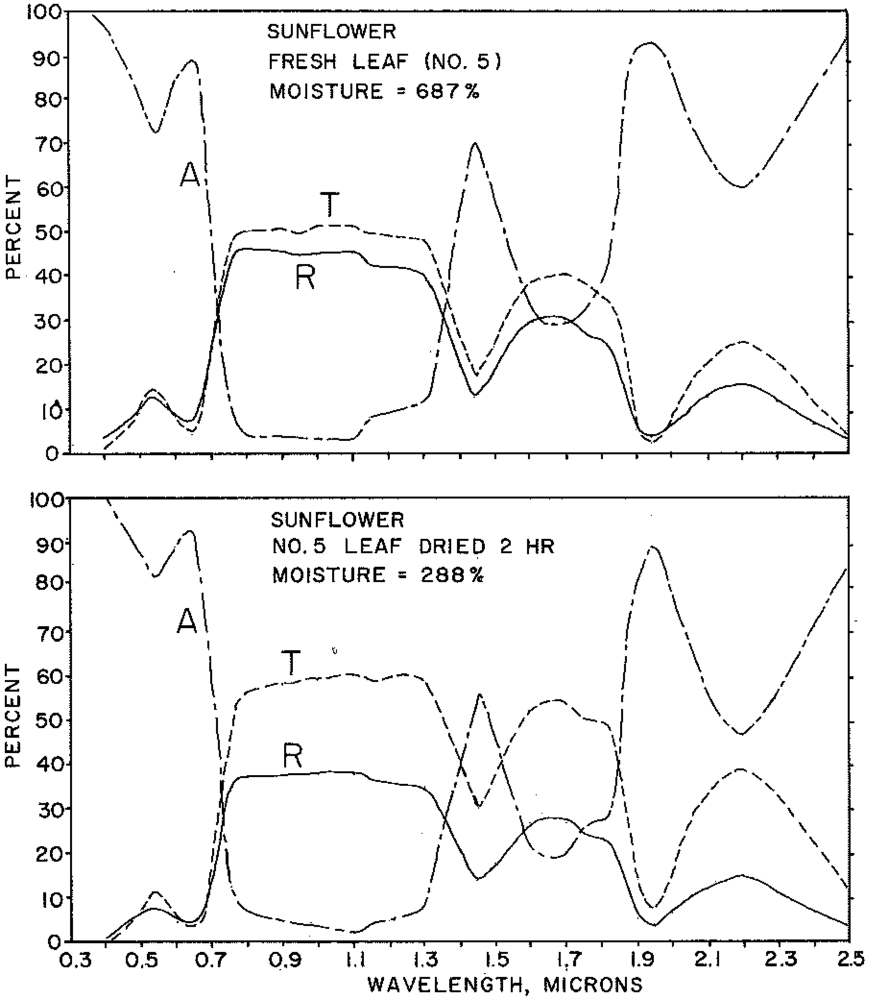

Fig. 3. Spectral characteristics – reflectance, transmittance, and absorptance – of fully turgid and partly-dried leaf of sunflower, *Helianthus annuus.* Though moisture content changes greatly in 2 hr., little change is evident in spectral properties.

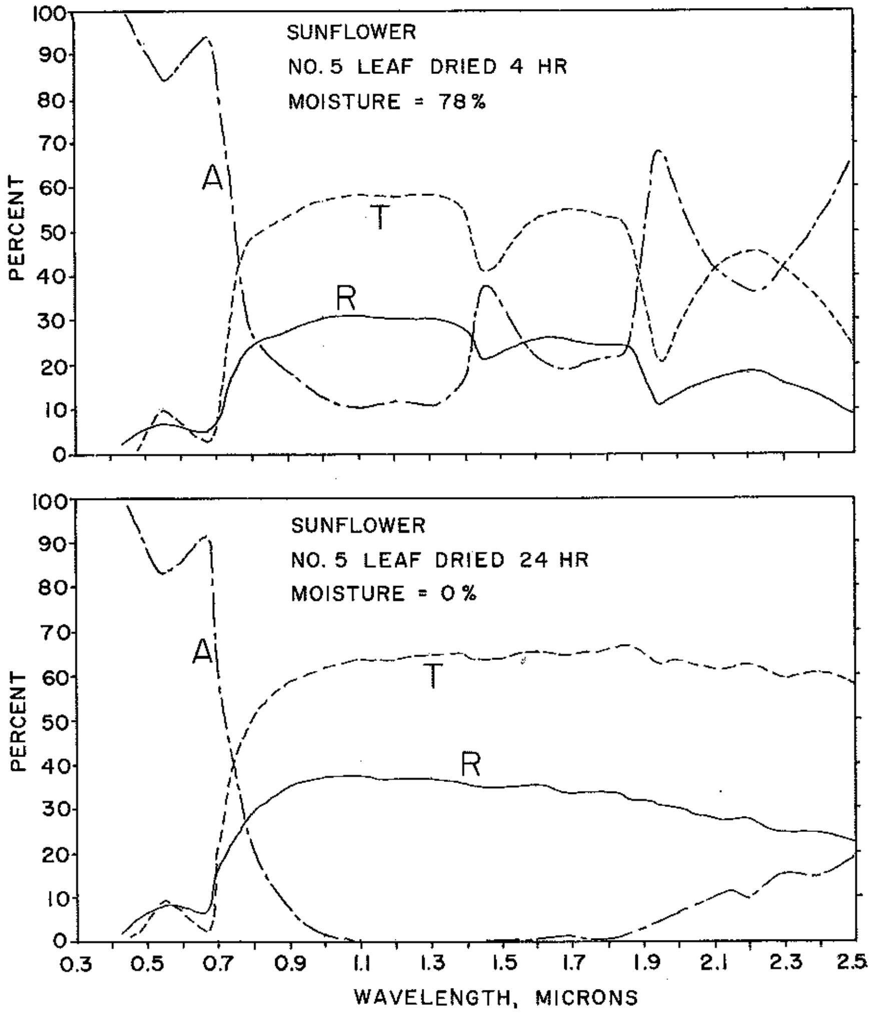

Fig. 4. Continued drying of sunflower leaf results in more significant changes in spectral properties. Note the increase in transmittance (T) and the decrease in reflectance (R) properties with desication of the leaf.

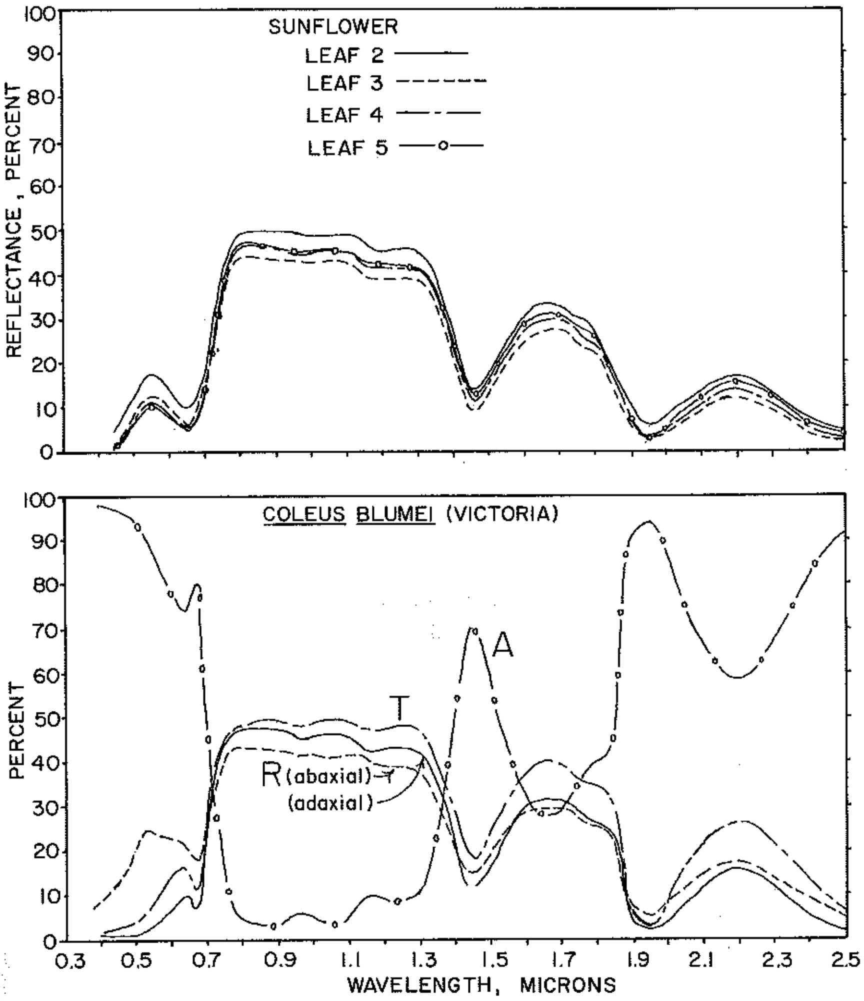

Fig. 5. Upper – Though different leaves of the same plant often contain different moisture contents and different quantities of chlorophyll, or protochlorophyll in very young leaves, reflectance properties of four leaves from the same sunflower plant are very similar. Leaf 2 is the oldest, leaf 5 is the youngest. Lower – *Coleus blumei* (Victoria) contains abundant anthocyanin in epidermal cells of the adaxial side of the leaf, but none in epidermal cells of the abaxial side. Reflectance comparisons of the two leaf sides show marked differences in the visible portion of the spectrum but much similarity in the infrared.

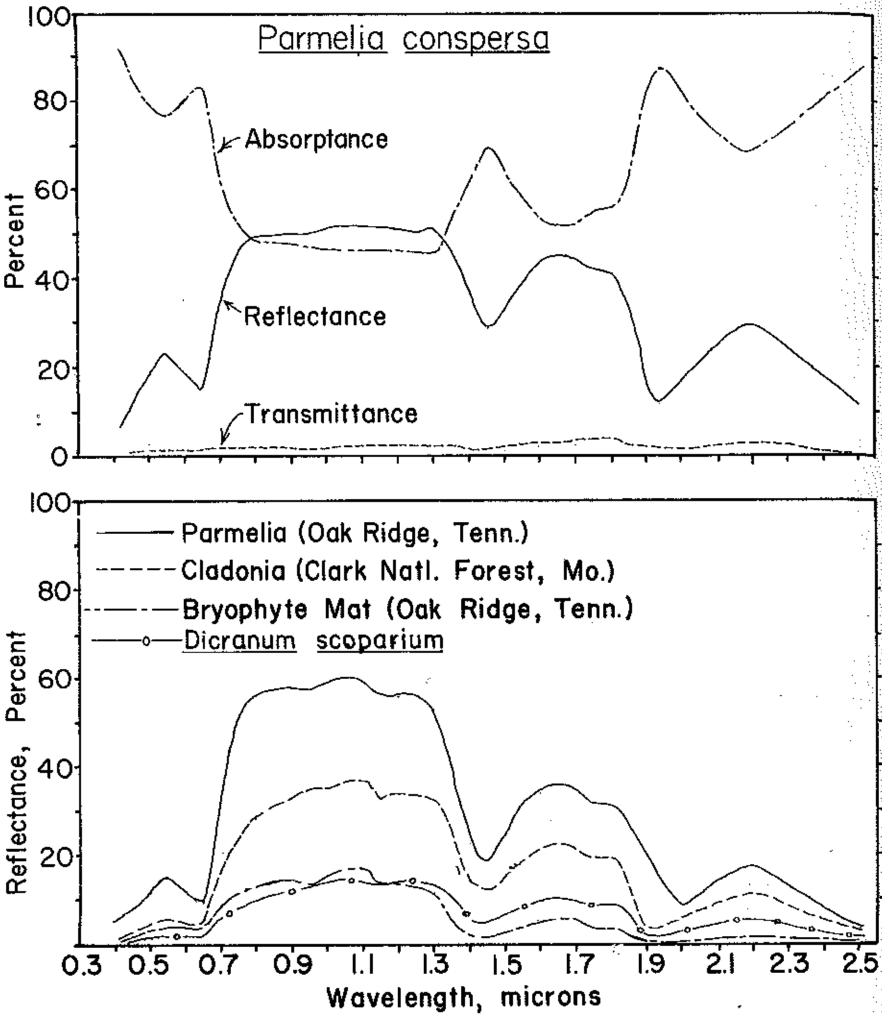

Fig. 6. Spectral properties of cryptogams are not dissimilar to those of flowering plants. There are however considerable differences in reflectance properties among certain cryptogams (below). Of Cladonia, the bryophyte mat, and *Dicranum scoparium*, the reflectance properties are of small segments of undisturbed mats taken from the habitats in which the plants were growing.