Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

Carbohydrate liquid crystals

George A. Jeffrey[a]; Lavinia M. Wingert[a]
[a] Department of Crystallography, University of Pittsburgh, Pittsburgh, Pennsylvania, U.S.A.

To cite this Article Jeffrey, George A. and Wingert, Lavinia M.(1992) 'Carbohydrate liquid crystals', Liquid Crystals, 12: 2, 179 — 202
To link to this Article: DOI: 10.1080/02678299208030392
URL: http://dx.doi.org/10.1080/02678299208030392

LIQUID CRYSTALS, 1992, VOL. 12, NO. 2, 179–202

Invited Article

Carbohydrate liquid crystals

by GEORGE A. JEFFREY* and LAVINIA M. WINGERT
Department of Crystallography, University of Pittsburgh,
Pittsburgh, Pennsylvania 15260, U.S.A.

(*Received 3 December 1991*)

There has been a marked increase during the past 5 years in the number of mesogenic compounds synthesized from the common, naturally occurring carbohydrates, particularly from glucose and glucitol. The structure of the mesophases depends on the shape of the molecules. Cyclic and acyclic carbohydrates with single *n*-alkyl or acyl chains of more than six carbon atoms are calamitic amphiphiles which form thermotropic smectic A_d phases. The more soluble of these mesogens are used as non-ionic surfactants for solubilizing and crystallizing membrane proteins. They form gels and lyotropic phases with water. The lamellar phase is most common, but some carbohydrate amphiphiles exhibit all of the classical lyotropic phases associated with the ionic surfactants, i.e. lamellar, cubic and hexagonal. Both the smectic A_d and the lamellar L_α phases are believed to be bilayers with interdigitized alkyl chains in the interior of the molecular clusters. The crystal structures of the alkylated cyclic sugars hitherto determined have head-to-head bilayers with interdigitizing alkyl chains. With the acyclic sugars, head-to-tail monolayer crystal structures are also observed. It is believed that these convert to bilayer structures prior to forming the bilayer smectic phases. Carbohydrates substituted with more than one hydrocarbon chain form hexagonal mesophases. Both cyclic and acyclic sugars, when monosubstituted with double alkyl or acyl chains, are wedge-shaped molecules which aggregate into discs that stack in hexagonally arranged columns. When full substituted, the flatter carbohydrate molecules, such as *scyllo*-inositol, form a large class of discotic mesophases. Those that are only partially substituted, leaving two hydroxyl groups free, are reported to form multilayer discotic mesophases which combine stacking forces with hydrogen bonding. The amphiphilic carbohydrates that form hexagonal phases thermotropically may form hexagonal, cubic or lamellar phases lyotropically.

1. Introduction

The breadth of carbohydrate chemistry and the versatility of synthetic methods that have been developed since the time of Emil Fischer [1] provide a basis for the synthesis of a very large number of carbohydrate amphiphiles [2–5]. The hydrophilic components of these amphiphiles are the naturally occurring mono-, di- and oligosaccharides, to which can be attached aliphatic or aromatic hydrophobic components in a variety of ways. These synthetic compounds can be purified and crystallized. This is in contrast to the naturally occurring glycolipids, such as the cord-factors [6, 7] and the carbohydrate-lipid components of bacterial lipopolysaccharides [8], which are often structurally heterogeneous and more difficult to purify and crystallize. The synthetic carbohydrate amphiphiles provide therefore a wide range of well-defined pure materials with which to study the often complex phase transitions associated with the liquid-crystalline state of matter. They permit the unusual opportunity to study the effect of varying the chemical constitution or configuration of

* Author for correspondence.

0267–8292/92 $3·00

one part of the amphiphile, while keeping the other part constant. The relationship between the consititution, configuration and functionality of the sugar component and the number and length of the hydrophobic chains neccessary to form the various types of thermotropic and lyotropic mesophase can be explored almost indefinitively, depending upon the interest and ingenuity of the carbohydrate chemists.

The structure and function of membranes has long been associated with lyotropic liquid-crystalline phases [9, 10]. Consequently, the biological scientists have developed a descriptive language for lyotropic mesophases which is different from that used by the physicists who are primarily concerned with thermotropic mesophases. Many carbohydrate amphiphiles form both lyotropic and thermotropic liquid crystals and so these compounds provide an opportunity to compare the structures of both types of mesophase formed from the same compound.

The practical use of these compounds as non-ionic surfactants for extracting and crystallizing membrane proteins stimulated many of the earlier syntheses [11, 12]. The first example, discovered in 1975 [13], was the highly soluble octyl β-D-glucopyranoside, which shows the classical lyotropic properties with water at room temperature that are associated with ionic surfactants [14].

Prior to 1982, there were only two publications, in 1938 and 1979, that drew attention to carbohydrates as a source of liquid crystals [15, 16]. The word carbohydrate does not appear in the indices of any of the major texts or compilations of data relating to liquid crystals published prior to 1982. In the past 5 years, the number of identified carbohydrate mesogens has increased from less than forty to several hundred. Much of this recent research has been concerned with the synthesis of new compounds and identification of thermotropic phases by differential scanning calorimetry measurements and optical microscopy. Less attention has been directed to the lyotropic phases, despite the insights that such studies might provide to the lyotropic phase behaviour of the components of biological membranes [17].

As with other mesogens that depend on strong polar interactions between their head groups, the carbohydrate mesogens show two endothermic peaks by DSC, a major enthalpy change of 2·5 to 100 kJ mol^{-1} at the melting point and a much smaller peak of less than 2 kJ mol^{-1} at the clearing point. Small enthalpic crystal–crystal phase transitions, which precede the melting point, are frequently observed. For some carbohydrate mesogens with short alkyl chains, the mesophase may only be observed on cooling from the melt. The liquid crystal phases are identified optically by their fluidity, birefringence, and lack of sharp crystal morphology. Not all of the investigators in this field are well-experienced in the morphological identification of liquid crystal phases [18], and identifying phases by testing for miscibility with known phases is rarely reported. X-ray diffraction is a third diagnostic tool that is not routinely used. Because mesophases are often metastable, and transient, the modern technologies of synchrotron and rotating anode X-ray sources in combination with area detectors has made X-ray studies more effective [14, 19, 20].

For some compounds, melting points differ on heating and cooling, and with the number of heating/cooling cycles. The melting points for a particular compound reported by different invesitgators may differ by as much as 10°C. More consistency is observed in the clearing points, where the measurements are usually within 1°C.

In this Invited Article, we focus on the molecular structures of the carbohydrate mesogens from the point of view of crystallographers and structural chemists. Molecules have more detail in their structures than indicated by the rods and discs frequently depicted in textbooks describing liquid crystals; they have size, shape and

functionality. Of the three components of molecular structure, constitution (formula), configuration (atom connectivity) and conformation (three dimensional shape), only the latter can change when molecules go from crystal to crystal to mesophase to liquid. Compared with crystals, liquid crystals provide very limited diffraction data and liquids provide even less. A knowledge of the molecular structure in the crystalline state is the only firm basis from which to speculate about the molecular structural changes that occur in going from the crystal to the liquid through an intermediate liquid-crystalline phase.

2. The constitutional domain of carbohydrate mesogens

Carbohydrates are defined as aliphatic polyhydroxy acids, alcohols, aldehydes, ketones, their derivatives and the oligomers and polymers thereof [21,22]. The simplest member is glyceraldehyde, but much of the emphasis in carbohydrate chemistry has traditionally been on the cyclic sugars (aldoses and ketoses) and the acyclic sugar alcohols (alditols) which are natural products and the building blocks of biologically important oligomers and polymers. The more commonly available of these natural products, such as glucose and glucitol, provide convenient and inexpensive starting compounds from which mesogens can be synthesized.

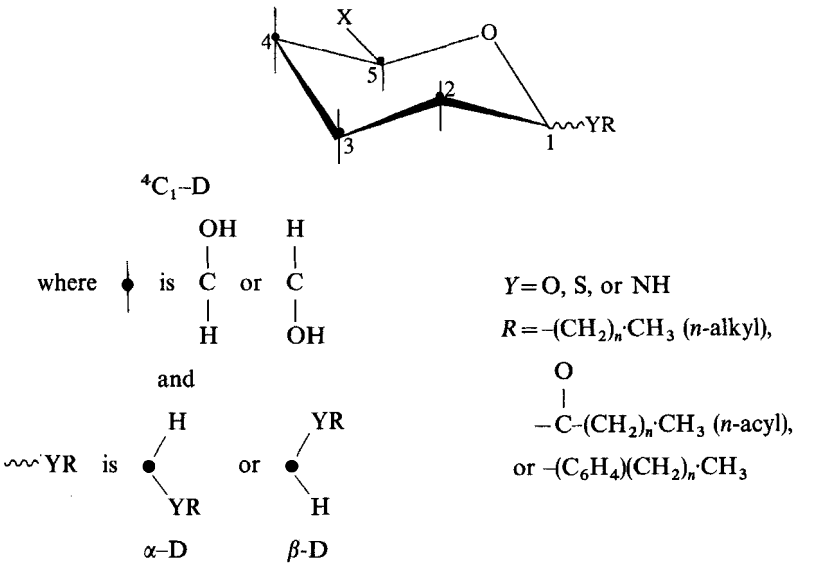
The amphiphilic mesogens are schizophrenic molecules. A constitutional requirement for amphiphilic mesogens is that the molecules consist of covalently linked moieties that separately would have different responses to changes in thermal energy or to solvation. Such molecules can be synthesized by linking one or more alkyl chains of appropriate length to a cyclic or acyclic sugar molecule. Thermotropic properties then result when the intermolecular forces between different parts of these amphiphilic molecules respond differently to thermal energy changes. In these amphiphiles, the alkyl chains interact by van der Waals forces and the carbohydrate moieties by hydrogen bonding. Lyotropic properties result from the different responses to the solvent, usually water, of the hydrophobic and hydrophilic moieties of amphiphilic molecules. Mesogenic thermal properties can also occur when all of the hydroxyl groups of a cyclic carbohydrate are equatorially oriented and substituted by alkyl chains. These disc-shaped molecules, which are not amphiphilic, form discotic liquid crystals with columnar hexagonal packing. With these molecules it is the difference in the van der Waals packing forces between the more rigid cores and the more flexible extentions of the molecules that produce the mesophase behaviour.

In the following sections, we discuss the molecular configurations of carbohydrates which have been shown to form mesophases. Many naturally occurring carbohydrates are chiral (with several different chiral centres), but no chiral mesophases (i.e. chiral smectic, chiral nematic or chiral discotic) have been observed. We therefore omit the chiral descriptors, D or L, from the names since this distinction is presently irrelevant. We are not aware of any evidence indicating a basic distinction between the mesophases formed by a chiral molecule, such as D-glucitol, and a meso molecule, such as galactitol.

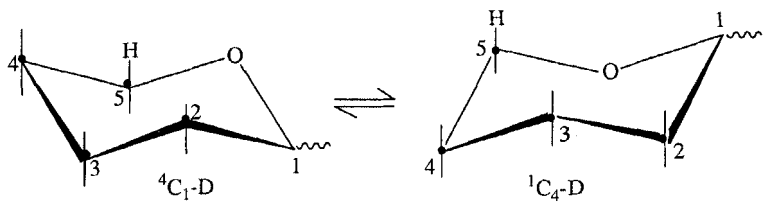
The 1,2-alkanediols [23(*a*)] and the 3-alkoxy, alkylthio and amino derivatives of 1,2-propanediol [23(*b*)] with alkyl groups from heptyl to tetradecyl have been shown to form thermotropic and lyotropic liquid crystals. Although not carbohydrates, they resemble them in being amphiphilic calamitic molecules with hydrogen-bonded head groups and in having properties similar to carbohydrate amphiphiles.

2.1. *Cyclic sugars with single alkyl chains*

The 1-*O*, 1-*S* and 1-*NH* *n*-alkyl or *n*-acyl glycopyranosides, **I**, are the carbohydrate mesogens that are the simplest to synthesize [24–30]. These may be pentoses ($X = H$), hexoses ($X = CH_2OH$), or hexuronic acids ($X = COOH$). Those commonly available are the pentoses (arabinose, ribose and xylose) and the hexoses (fructose, galactose, glucose and mannose). *R* can range from C_7H_{15} to $C_{20}H_{41}$ and possibly higher. Some free hydroxyl groups on the sugar component are necessary, but it is not certain how many. When $X = CH_2OH$ or COOH, the most stable chair conformation is $^4C_1$, as shown in **Ia**, since this places the bulky *X* group in an equatorial orientation with respect to the sugar ring. When $X = H$, as in ribopyronosides, an equilibrium between $^4C_1$ and $^1C_4$ chair conformations, as in **Ib** can exist in solution [21], and either may be present in the crystalline or liquid-crystalline state, depending upon the configuration of the pentose. Included in this class are the reducing di- and oligosaccharides, where the *R* group is attached via 1-*O* or 1-*S* of the reducing monosaccharide moiety. All of the compounds of this class that have been examined optically are reported to form smectic A_d mesophases with melting points in the range from 42°C (for octyl 1-*S*-*β*-glucopyranoside) [30] to 183°C (for the disaccharide derivative tetradecyl 1-*O*-*β*-lactoside) [31]. The clearing points are in the range from 69°C (for heptyl 1-*O*-*β*-glucopyranoside) to >249°C (for tetradecyl 1-*O*-*α*-lactoside). A table of the data for many of these compounds is available in [31]. The melting and clearing points for a



Ia



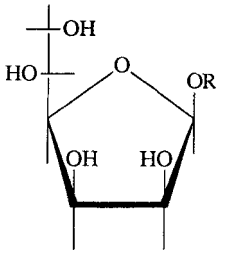
Ib

(It is common practice with carbohydrate formulae to omit the methylene C–H hydrogen atoms.)

series of 1-*O*, 1-*S* alkyl pyranosides are shown in figure 1 (*a*) [30]. A notable feature is that the clearing points rise more rapidly and regularly with alkyl chain length. This is even more obvious in the acyclic sugar derivatives shown in figure 1 (*c*). The melting points of some compounds, but not all, show an even-odd effect with alkyl chain length. In the *n*-alkyl gluconamides, discussed in § 2.4, this is associated with different crystal structures.

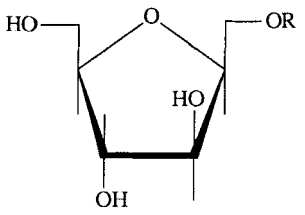
Of the 1-*NH* alkyl glucopyranosides, the hydroxyl group on C(2) must be absent since only the 2-deoxy compounds are sufficiently stable on heating to permit quantitative measurements [32]. These 1-amino-2-deoxy-β-glucopyranosides with alkyl chains from nonyl to hexadecyl are monotropic, exhibiting liquid-crystallinity only on cooling. Unlike the other *n*-alkyl glycosides, there is no regular increment with alkyl chain length for either the melting or clearing points. The melting points are in the range 87 to 105°C, while the clearing points are 73 to 90°C.

An aromatic ring can be included with the alkyl chain without disrupting the mesogenic properties. 1-*O*-α- and β-glucopyranosides with *R* of $-C_6H_4{\cdot}C_3H_7$, $-C_6H_4{\cdot}C_4H_9$, $-C_6H_4{\cdot}C_7H_{15}$ form thermotropic and lyotropic liquid crystals. The thermotropic melting points are 145–150°C for the α series and 110–150°C for the β compounds [33]. An analogous series with furanose sugar rings has been synthesized and shown to be mesogenic. These are the 1-*O*-*n*-alkyl-β-mannofuranosides, **II** [34], the 1-*O*-*n*-alkyl-2,5-anhydro hexitols of glucitol, **III** [35], and iditol, **IV** [35]. The shorter alkyl chain members, i.e. C_7H_{15} to C_9H_{19} for **III** and C_7H_{15} for **IV** are liquid crystals at room temperatures. Both the melting and clearing points, as shown in figure 1 (*b*), increase with alkyl chain length, the latter increasing more rapidly. As with glucopyranoside derivatives, the melting points of the mannofuranoside derivatives show an odd-even effect. The clearing points rise more smoothly, irrespective of whether *n* is even or odd. While these trends are similar for both groups of compounds, the furanose ring compounds have melting points and clearing points about 30°C lower than those of the pyranosides.



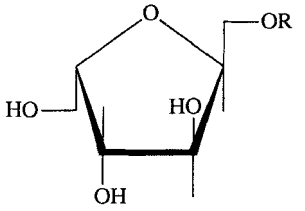
II

$R = C_7H_{15}$ to $C_{16}H_{33}$



III

$R = C_7H_{15}$ to $C_{18}H_{37}$



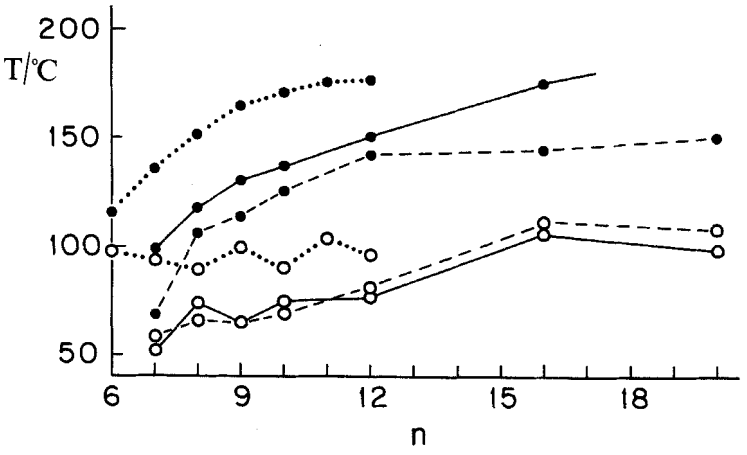
IV

$R = C_7H_{15}$ to $C_{18}H_{37}$

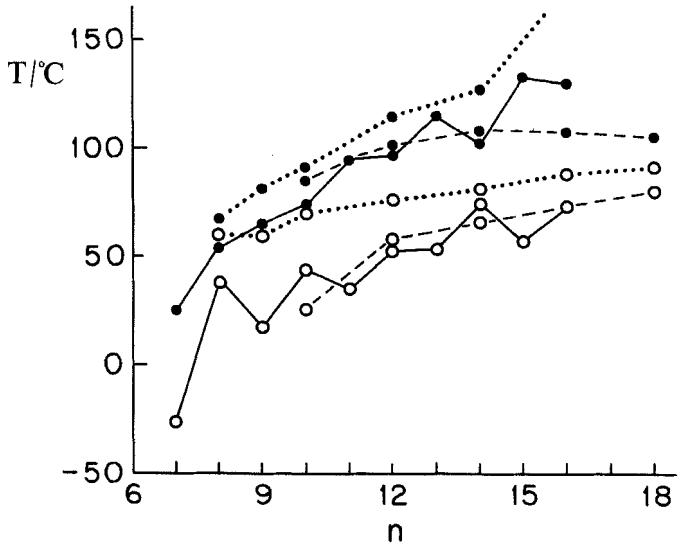
The morphology and the X-ray diffraction patterns, when reported for these compounds, indicate that, without exception, the mesophases are smectic A_d. As with the pyranosides, the *d* spacing of the intense X-ray diffraction ring, which is a characteristic of the smectic A_d phase, is that of a bilayer with thickness 1·5 to 1·7 times the calculated length of a fully extended single molecule. Two models are proposed for this smectic A_d mesophase, shown diagrammatically in figure 2. Relatively small changes in melting points and regular increases in clearing points with increasing chain length favours model II in which the alkyl chains form the core of the mesophase bilayer, with the sugar moieties on the exterior, as in the lamellar lyotropic phases. This

is consistent with the view that the hydrogen bonds between the sugar moieties are more sensitive to increase of thermal energy than are the van der Waals forces between the interdigitizing alkyl chains. Hydrogen bonds are weakened by increased oscillation about the individual C–O–H bonds. (This is not so for N–H...O hydrogen bonds, which are less sensitive to thermal motion.) We visualise, therefore, that the static system of strong O–H···O bonds in the crystal are replaced by a weaker, dynamic system of bonds with increase of temperature, as between ice and water. In contrast, increased thermal motion in the alkyl chains involves a concerted motion of segments of the chains, allowing much of the interaction energy to be retained [36].

The distinction between the increments in the two transition temperatures is more obvious with the straight chain glucitol derivatives than with the cyclic pyranosides and furanosides, as shown in figure 1. The 1,2-alkanediols, which have smaller head groups with only two hydroxyls, have both melting points and clearing points which



(*a*)



(*b*)

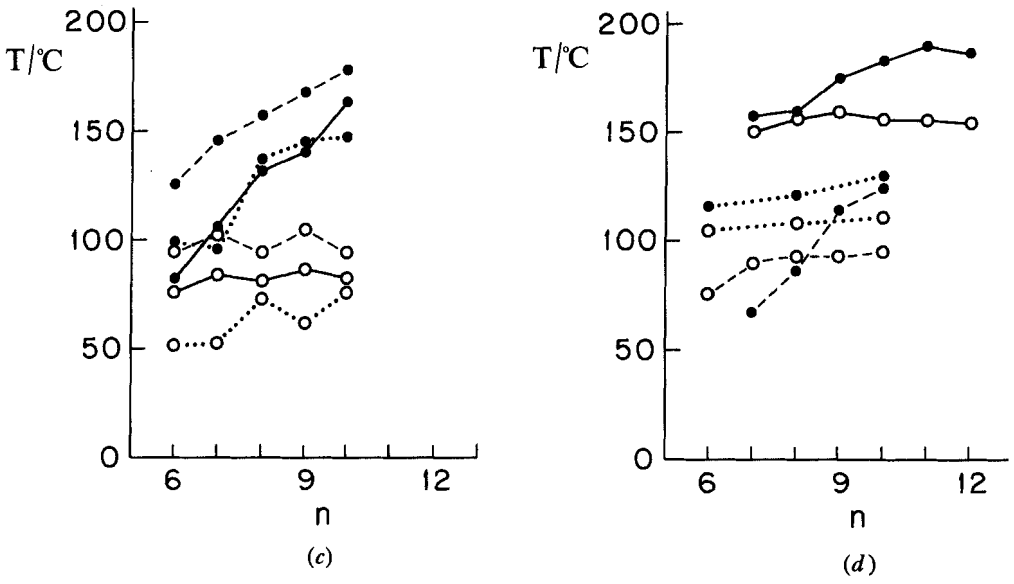
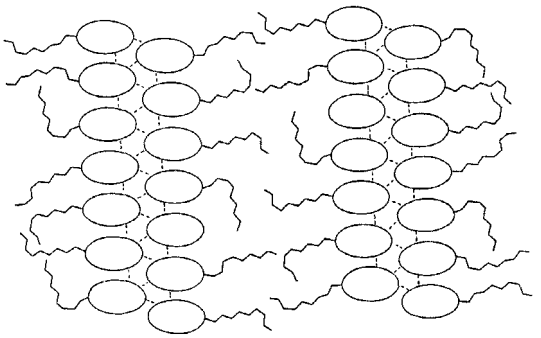


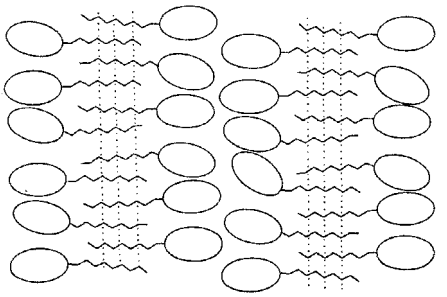
Figure 1. The dependence of melting (○) and clearing points (●) on alkyl chain lengths for some carbohydrate mesogens. (*a*) Solid line: 1-*On*-alkyl-α-glucopyranosides (**I**); dashed line: 1-*O*-*n*-alkyl-β-glucopyranosides (**I**); dotted line: 1-*S*-*n*-alkyl-α-glucopyranosides (**I**). (*b*) Solid line: 1-*O*-*n*-alkyl-β-mannofuranoside (**II**); dashed line: 1-*O*-*n*-alkyl-2,5-anhydro glucitol (**III**); dotted line: 1-*O*-*n*-alkyl-2,5-anhydro iditol (**IV**). (*c*) Solid line: 1-*O*-*n*-alkyl-1-deoxy glucitols (**X**); dashed line: 1-*S*-*n*-alkyl-1-deoxy glucitols (**XI**); dotted line: 6-*O*-*n*-alkyl-6-deoxy glucitols (1-*O*-deoxy gulitols). (*d*) Solid line: *n*-alkyl gluconamides (**XIV**); dashed line: 1-deoxy-(*N*-methyl alkanamido)-glucitols (**XV**); dotted line: *N*-methyl alkanamido ethyl gluconamides (**XVI**).

rise steadily with alkyl chain length [23a]. The choice of model II is therefore a hypothesis that may differ with class of head group and needs to be tested by some different experimental criteria.

The lyotropic properties of the carbohydrate mesogens are less frequently studied since they involve variation of both temperature and concentration in water and the construction of phase diagrams. Carbohydrates, being hydrophilic molecules, are generally soluble in cold water, but the solubility of the alkylated carbohydrates is unpredictable. Octyl 1-*O*-α-glucopyranoside (α-OG) is only slightly soluble in cold water, whereas octyl 1-*O*-β-glucopyranoside (β-OG) is very soluble. Lyotropic phases are formed by alkylated glucosides that are sufficiently soluble and also have alkyl chains as long as C_6H_{13} or higher. The solubility of β-OG at room temperature is such that penetration of the crystalline powder by water occurs over 15 to 30 min. This allows sufficient time for measurement of the X-ray diffraction pattern of each sequentially formed mesophase—lamellar (L_α), cubic (V_1) and hexagonal (H_1)—and of the micellar solution as the dilution increases [14]. For the heptyl compound, a lamellar mesophase is observed only briefly at room temperature as the powder dissolves rapidly; however, at 0°C all three mesophases are observed. For hexyl and shorter chains, no mesophases have been observed [14]. Other investigators report three mesophases for the heptyl, octyl and nonyl derivatives, but not for the longer chains [37].



(*a*)



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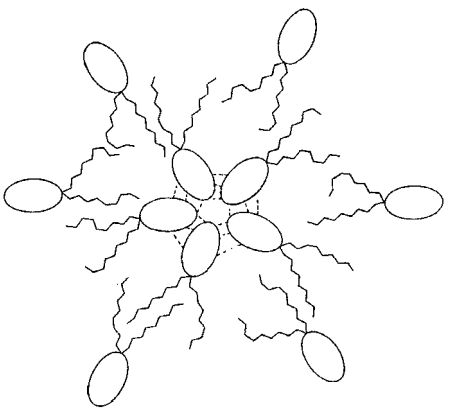


(*c*)

Figure 2. Hypothetical models for carbohydrate mesogens. (*a*) Smectic A_d. Model I. Dashed lines represent static hydrogen bonds. (*b*) Smectic A_d. Model II. Dotted lines represent optimum van der Waals interactions. (*c*) Columnar hexagonal.

The highly viscous cubic phase of β-OG gives discrete Bragg diffraction spectra superimposed on a broad diffuse ring similar to that from the micellar solution. This corresponds to ordered domains, greater 1000 Å in diameter, in a viscous solution or gel. In the hexagonal mesophase, the increased solvation of the head groups forms wedge-shaped solvated molecules which aggregate into columns with hexagonal packing [14].

A deuterium NMR study of the lyotropic phases of α-OG and β-OG shows characteristic spectra for each of the three mesophases. This provides a method for the determinations of their temperature/concentration ranges [38].

A study of the lyotropic properties of the disaccharide derivative, dodecyl 1-*O*-maltoside, by X-ray diffraction showed the lamellar phase changing to hexagonal with increased dilution. No intermediate cubic phase was reported [39]. A characteristic of the 1-*O*-α-, 1-*O*-β- and 1-*S*-α-glucopyranosides with alkyl chains of $C_{12}H_{25}$ and longer is the spontaneous formation of myelins. These are mobile tubular structures formed at the interface with the aqueous phases, as shown in figure 3. These tubules, which are visible by optical microscopy, have diameters up to $3{\cdot}5 \times 10^5$ Å (35 μm) and can be over a mm in length. Myelins appear to be cylindrical or helical arrangements of many (300–5000) of the bilayers that constitute the lamellar phase [40, 40(a)].

Since lyotropic mesophase formation requires that the water penetrate the solid, the state of aggregation is significant. It is observed that lyotropic mesophases are formed at lower temperature from a super-cooled thermotropic smectic phase than from the crystalline powder or single crystals [41]. This is consistent with model II for both smectic A_d and lamellar L_α phases in which the polar head groups are on the outside of the bilayers [42].

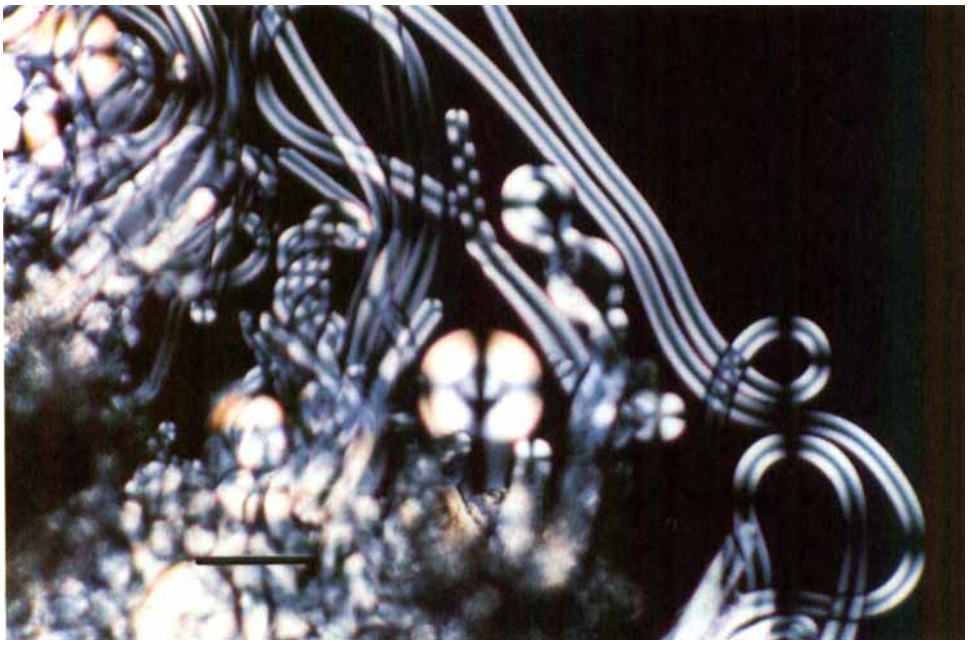
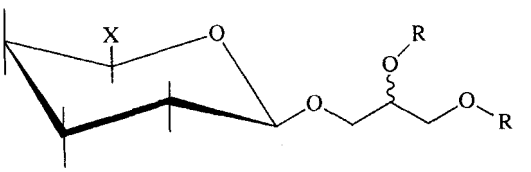


Figure 3. Myelins formed by 1,2-di-*O*-decyl-3-*O*-(β-D-glucopyranosyl)-glycerol and water at 20°C; photographed between crossed polarizers. The scale bar represents 0·050 mm (50 μm).

Another source of starting materials for carbohydrate mesogens are the cyclitols or inositols, 1,2,3,4,5,6-cyclohexane hexols, of which there are nine isomers. These molecules resemble the pyranose sugars except for the ring oxygen being replaced by a CHOH group. The most naturally occurring cyclitol is *myo*-inositol with one axial and five equatorial hydroxyls. No mesogenic inositols substituted with single alkyl chains have been reported, but inositols with double alkyl chains are mesogenic. These are described in the following section.

2.2. *Cyclic sugars with two geminal alkyl chains*

In compound **V**, two chains are linked through glycerol to C(1) of α- or β-galacto- or glucopyranose. The acyl compounds, which are referred to as 1,2-di-*O*-acyl-3-*O*-glycosyl-*sn*-glycerols, are related to the biologically important phospho- and sphringolipids. The mesogenic phases of aqueous dispersions of these glycerol derivatives have been studied extensively by a variety of methods for the α and β series of glucopyranosides with chain lengths from $C_{10}H_{21}$ to $C_{20}H_{41}$ [43–46(a)] and for the β-galactosyl derivatives in the even series from $C_{12}H_{23}$ to $C_{18}H_{37}$ [46]. The phase behaviour appears to be more complex than for the single chain glycosides and more sensitive to heating and cooling rates and to the effects of preheating. In addition to a bilayer phase, these compounds form cubic or hexagonal phases when heated after annealing at low temperature. This is more common for the β series than for the α. Those with chain lengths up to $C_{16}H_{33}$ form cubic phases. With longer chains, the mesophases are hexagonal with the acyl chains on the exterior of hexagonally packed columns, i.e. inverted hexagonal, H_{II}.



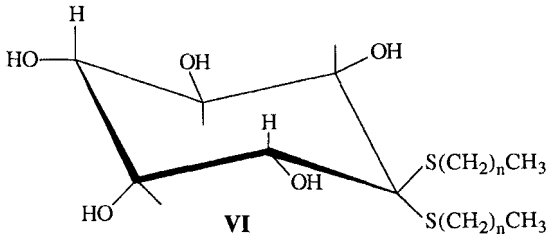
V R = alkyl or acyl

The alkyl compounds **V**, with chain lengths of 10 or more carbons, form myelins at temperatures that increase with alkyl chain length. The myelins occur when there is a sufficiently high ratio of alkyl chain carbons to the number of –OH and =O substituents on the polar head groups of amphiphilic carbohydrate molecules. For molecules with two alkyl chains, the number of carbons per chain required for myelin formation is lower than for molecules with a single alkyl chain. At higher temperatures, the birefringent bilayer structure of myelins often converts to a non-birefringent cubic phase or to the hexagonal phase [40, 40(a)].

The penetration by water into samples of the double-chain compounds occurs at about the same temperature whether the dry sample is a crystal or a super-cooled liquid crystal. The explanation for this is that the super-cooled thermotropic mesophase of these compounds is the inverted hexagonal in which the polar head groups in the interior are not readily accessible to water (as they are in smectic phases of single chain amphiphiles). Thus, the ability of water to penetrate these samples is not enhanced in the liquid-crystalline state over the crystalline state [41].

The 1,1-*S*,*S*-dialkyl derivatives of *scyllo*-inositol, **VI**, with alkyl chains from C_7H_{15} to C_9H_{19}, are reported to form cubic M_I and hexagonal H_x mesophases with transition temperatures in the range 130 to 185°C[47]. With these compounds, the transition

temperatures decrease with increase of alkyl chain length. It is argued that since the molecules are Y-shaped, due to the double side chains, they form disc-like molecular clusters with the carbohydrate component at the centre as shown in figure 2(*c*). This type of mesophase structure is also reported for the acyclic *S,S,*-dialkyl derivatives discussed in 2.5.

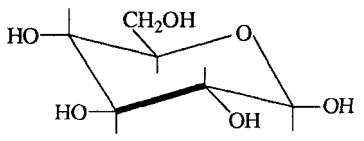


VI

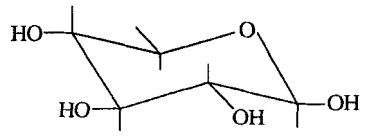
2.3. *Cyclic sugars with fully substituted hydroxyl groups*

When the all-equatorial pyranose sugars such as *β*-glucopyranose (**VII**) and *β*-xylopyranose (**VIII**) and the cyclitol, *scyllo*-inositol (**IX**), are fully substituted by *O*-alkyl or *O*-acyl chains, a disc-shaped molecule is obtained, analogous in shape to the original discogens, the benzene alkanates [48]. (In this context alkyl or acyl derivatives of the flat ascorbic acid molecules would seem to be worth investigating.) Since 1984, research on these compounds has resulted in a rich, and sometimes confusing, literature [49–64]. Discotic liquid crystal mesogens derived from *scyllo*-inositol (**IX**) have also been synthesized with one of the hydroxyl groups substituted by other groups, such as $S\text{–}CH_2\text{–}C_6H_5$, $SO_2{\cdot}CH_2{\cdot}C_6H_5$, N_3 and $NHCOCH_3$ [52–56]. The all-equatorial derivatives of the di- and trisaccharides, cellobiose and cellotriose, substituted with COC_9H_{19} are also reported to form discotic mesophases [60]. Pentaalkanoyl *α*- and *β*-glucopyranoses are reported to form chiral discotic mesphases [61, 62], but this claim has been disputed [49, 50, 63]. Hexa acyl scyllo inositols are reported to form mesophases but penta acyl *β*-glucopyranosides do not; neither does alkylated *cis*-phloroglucitol, which is a 2,3,5-cyclohexane triol with all three hydroxyl groups equatorial [50]. Fully substituted *myo*-inositol, which has one axial hydroxyl group, and mytilitol, which has an axial $-CH_3$ group, do not form mesophases [56]. Presumably the axial group inhibits the effective discotic packing of the molecules.

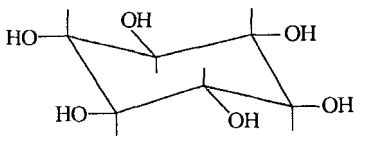
The discotic mesophases give X-ray diffraction patterns showing a single intense inner ring and a more diffuse outer ring. Distinguishing between various ways of ordering columnar molecular clusters [58] depends upon obtaining oriented samples.



VII



VIII



IX

Magnetically oriented hexa-*O*-decanoyl *scyllo*-inositol was identified as forming a D_{ho} phase, [59], with the sugar moiety at the interior of the columns. The melting points of these discotics are generally in the same temperature ranges as for the calamitic mesogens, but the clearing points tend to be higher. It is interesting to note that the melting points vary, while the clearing points tend to remain constant with increase of alkyl chain length. This is the opposite to that observed with the calamitic mesogens.

Recent research on derivatives of *scyllo*- and *myo*-inositol, in which two of the hydroxyl groups are unsubstituted, suggests that there is yet another large class of discotic liquid crystals in which the hydrogen bonding between the discs results in the formation of multilayer mesophases [64].

2.4. *Acylic sugars with single alkyl chains*

Alkyl derivatives of the alditols (sugar alcohols), $CH_2OH{\cdot}(CHOH)_mCH_2OH$, are another source of mesogens. There are two tetritols ($m=2$), four pentitols ($m=3$) and six hexitols ($m=4$). Erythritol, threitol ($m=2$), ribitol, xylitol ($m=3$) and galactitol, glucitol, mannitol ($m=4$) are the common natural products. Some of these compounds are useful as non-ionic surfactants for crystallizing membrane proteins and this has prompted an active interest in both their synthesis and their physical properties. Terminal *n*-alkyl chains have been attached to the alditols—ribitol, gluctitol and mannitol—in a variety of different ways to form calamatic molecules with thermotropic and lyotropic properties. These have been examined for compounds with 1-*O*, 1-*S* or 1-*NH* linkages between the carbohydrate and alkyl chains, as in

$$CH_3(CH_2)_nO{\cdot}CH_2{\cdot}(CHOH)_m{\cdot}CH_2OH, \quad \textbf{(X)}$$

$$CH_3(CH_2)_nS{\cdot}CH_2{\cdot}(CHOH)_m{\cdot}CH_2OH, \quad \textbf{(XI)}$$

$$CH_3(CH_2)_nNH{\cdot}CH_2{\cdot}(CHOH)_m{\cdot}CH_2OH. \quad \textbf{(XII)}$$

Thermotropic liquid crystals have been observed for the 1-*O*, 1-deoxy glucitol and mannitol derivatives, **X**, with $n=6$–10 and 6–16, respectively, and for the 1-*S* derivatives of 1-deoxy glucitol, **XI**, with $n=6$–10 [65, 66]. The 1-(*n*-alkylamino)-1-deoxy glucitols **XII** with $n=7$ to 16 form mesophases. In these compounds the melting points are almost independent of the chain length (124–128°C) while the clearing points rise steadily from 114°C to 173°C for $n=7$ to 12, then remain constant [32]. Removal of a hydroxyl group in the 1-(*n*-alkylamino)-1,2-dideoxy glucitols lowers the transition temperatures by about 20°C. The substitution of a methyl group on the NH lowers both melting and clearing points, presumably due to elimination of the potential for NH···O hydrogen bonding [32].

Mesophases are also reported for 6-*O* and 4-*O* *n*-alkyl glucitols with $n=6$–10 [67], The latter, which form liquid crystals below room temperature, are not linear molecules; in consequence, the report [67] that they form smectic phases is unexpected. The inclusion of a hydroxyl group at the terminus of the alkyl chain linked to mannitol is reported not to inhibit mesophase formation [68]. The double-headed di-mannityl derivatives, **XII**, with $n=16$ and 22, are reported to be mesogenic [68]:

$$CH_2OH(CHOH)_4O(CH_2)_nO(CHOH)_4CH_2OH. \quad \textbf{(XIII)}$$

Compounds with the alkyl chains linked directly to the alditol have been synthesized for $CH_3(CH_2)_{12}$ 1-deoxy lyxitol, ribitol and xylitol. Some of these compounds are reported to have double melting points but were not examined further [69, 70]. The

alkyl chains have also been linked to the alditol through an amido group in the *N*-(*n*-alkyl)-aldonamides, **XIV**, and in the 1-deoxy-(*N*-methyl-alkanamido) alditols, **XV**:

$$CH_3(CH_2)_n{\cdot}NH{\cdot}CO{\cdot}(CHOH)_m{\cdot}CH_2OH, \qquad \textbf{(XIV)}$$

$$CH_3(CH_2)_nCO{\cdot}N(CH_3){\cdot}CH_2{\cdot}(CHOH)_m{\cdot}CH_2OH. \qquad \textbf{(XV)}$$

These linkages can be compared in the schemes:

alditol	alditol	alditol
|	|	|
O, S, NH	C=O	N–CH_3
|	|	|
alkyl chain	HN	C=O
	|	|
	alkyl chain	alkyl chain
X-XII	**XIV**	**XV**

In the aldonamide series, **XIV**, smectic A_d mesophases have been reported for *n*-decyl ribonamide ($m=3$) [71] and the *n*-alkyl gluconamides with $m=4$, $n=7$–12, 18 [72]. In the *N*-methyl alkanamido series, **XV**, mesophases have been reported for the 1-deoxy glucitols witn $n=7$–12 and 18. These compounds have the acronym MEGA-*N* (where $N=n+2$). Both compounds **XIV** and **XV** have been shown by optical properties and X-ray diffraction to form smectic A_d phases [73]. Again the melting and clearing points are lower for the MEGA compounds (**XV**) than for the aldonamides (**XIV**) because of the absence in the MEGA compounds of NH···O=C hydrogen bonding. The thermotropic properties of MEGA-8, 1-deoxy-(*N*-methyl-octanamido)-glucitol, have been studied in detail by calorimetry, microscopy and X-ray diffraction to reveal three crystal phases in addition to the smectic liquid crystal between 78°C and 88°C [74].

$$CH_3(CH_2)_nCO{\cdot}N{\cdot}(CH_2)_2{\cdot}NH{\cdot}CO{\cdot}(CHOH)_4CH_2OH \qquad \textbf{(XVI)}$$
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad |$$
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad CH_3$$

Components of **XIV** and **XV** were combined to give *N*-methyl alkylamido ethyl gluconamides, **XVI**, for $n=4$, 6 and 8 [73]. These compounds form mesophases in which the melting points and clearing points run parallel (see figure 1 (*d*)). The lyotropic properties of the alkanamido compounds of 1-deoxy glucitol, **XV**, have been studied by calorimetry and optical microscopy and phase diagrams have been constructed for $n=6$ to 10 (octanamido to dodecanamido), and for a C_{18} oleoyl derivative [37]. The octanamido compound ($n=6$) forms only the hexagonal H_I phase while the C_{18} oleoyl compound forms only the lamellar, L_α phase. The other compounds in the series form all three phases—lamellar L_α, cubic V and hexagonal H_I.

These results can be related to the molecular shapes. A hydrated amphiphile with a single short chain has a wedge shape that packs to form hexagonally arranged columns of discs, each made up of several molecules that fit together like the pieces of a pie. This is the case for MEGA-8 with a C_7 alkyl chain which forms only the hexagonal lyomesophase. An amphiphile with a long hydrocarbon chain, such as the C_{18} oleoyl derivative of the MEGA series, has a more rod-like shape and forms only the lamellar lyomesophase. Intermediate chain lengths of the MEGA series form both the hexagonal and the lamellar mesophases, as well as the intermediate cubic mesophase,

Table 1. Calorimetrically determined melting points (T_m)† and clearing points (T_c)‡ of 1,1-*S*,*S*-di-*n*-alkyl-1-deoxy-alditols.

		C_4H_9		C_5H_{11}		C_6H_{12}		C_7H_{15}		C_8H_{17}		C_9H_{19}		$C_{10}H_{21}$	
	Refs	T_m/°C	T_c/°C	T_m/°C	T_c/°C	T_m/°C	T_c/°C	T_m/°C	T_c/°C	T_m/°C	T_c/°C	T_m/°C	T_c/°C	T_m/°C	T_c/°C
Derivatives of Pentitols:															
Arabinitol	[82]									83	102			87	104
	[83]									88	104				
	[85]	107	—	95	—	94	(85)	92	96	88	102	88	104	87	105
	[84, 86]									93	101				
Lyxitol	[82]									56	104			64	110
	[83, 85]	75	—	70	(68)	65	86	67	98	64	104	67	107	66	108
	[84]									65	103				
Ribitol	[84]									41	95				
	[85]	48	—	3	46	6	83	43	89	39	99	41	98	49	105
Xylitol	[82]							<0	78	<0	77				
	[83]					<RT	61	<RT	79	*c*.RT	110				
	[85]	<0	—	<0	37	<0	68	9	79	21	88	44	96	41	86
	[84, 86]									38	84				
2-Deoxy-ribitol	[85]	<20	29	<20	54	<20	66	<20	75	<20	83	<20	84	<20	76

Derivatives of Hexitols:															
Galactitol	[82]							115	137	111	143				
	[83,85]	126	—	119	(109)	116	126	115	136	112	142	110	145	109	147
	[84]									113	142				
Mannitol	[82]					113	118	110	135	110	144	107	139	111	152
	[83]									114	145				
	[85]	117	—	117	(102)	117	121	116	135	114	143	113	148	111	151
	[84,86]			117	(102)	117	121	116	135	114	143	112	148	111	151
Glucitol	[82]									100	119			97	132
	[83]	127	—	116	—	103	—	102	104	100	117	100	131	98	133
	[85]	126	—	116	—	104	—	103	105	100	117	100	126	98	131
	[84,86]			115	—	103	—	103	105	102	118	101	126	95	131
2-Deoxy-Glucitol	[85]	136	—	120	—	113	—	114	(110)	112	117	112	120	113	122
	[84,86]									112	118				
Derivative of a Hepititol:															
Glucogulitol	[84,86]									119	163				

† RT = room temperature.
‡ Values in parentheses observed on cooling;—indicates no mesophase observed on heating or cooling.

at different solvent concentrations. The observation that these acyclic mesogens form hexagonal and cubic mesophases over wider ranges of chain length and temperature than do the cyclic alkyl glucosides is explained in terms of the greater conformational freedom of the alditol moieties, which allows a wider range of head groups and more extensive hydration [37].

The alkyl gluconamides, **XIV**, form gels which have been studied extensively by viscosity measurements and electron microscopy [75–81]. Electron microscopy reveals networks of fibrous aggregates with diameters of between 40 and 500 Å and lengths of the order of several μm which are similar to those observed in the gels from bacterial polysaccharides. These are precursors to very thin crystals (whiskers) or long strings of microcrystals formed when these metastable gels equilibrate. These amphiphilic molecules are believed to self-associate into bilayer sheets which then fold or curl to form helical tubes.

Compounds with an amino linkage (**XII**) or a methylated amino linkage form myelin figures if the ratio of the number of alkyl chain carbons to the number of –OH groups is sufficiently high. Compounds with the methylated amide linkage (**XV**) and alkyl chain lengths less than C_{15} do not form myelin figures, but may do so with longer chains [42].

2.5. *Acyclic sugars with two geminal alkyl chains*

Three independent groups [82–86] have reported studies of the 1,1-*S*,*S*-di-*n*-alkyl-1-deoxy-alditols, in which both the sugar and the alkyl chain lengths are varied. These compounds, **XVII**, also referred to as aldose dialkyl dithioacetals because they are synthesized from aldoses rather than alditols, are derivatives of the four pentitols ($m=3$), three hexitols ($m=4$) and a hepitol ($m=5$). The melting points and clearing points of the compound are given in table 1. Data on the thermotropic behaviour of 2-deoxy derivatives of ribitol and glucitol, **XVIII**, are also given in table 1. This is one of the more complete studies of a series of related compounds hitherto reported and permits an analysis both of the consistency of the data amongst different observers and of the effect of changes in consitution and configuration on the thermotropic properties. Throughout these series, the melting points tend to remain constant or drop with increasing chain length, while the clearing points rise. There is no, or only a very slight, odd-even effect. The recrystallization temperatures drop with increase of chain lengths and the interval between the melting point and recrystallization point is relatively small and fairly constant. The agreement between independent investigators is good, except for the di-octyl xylitol compound.

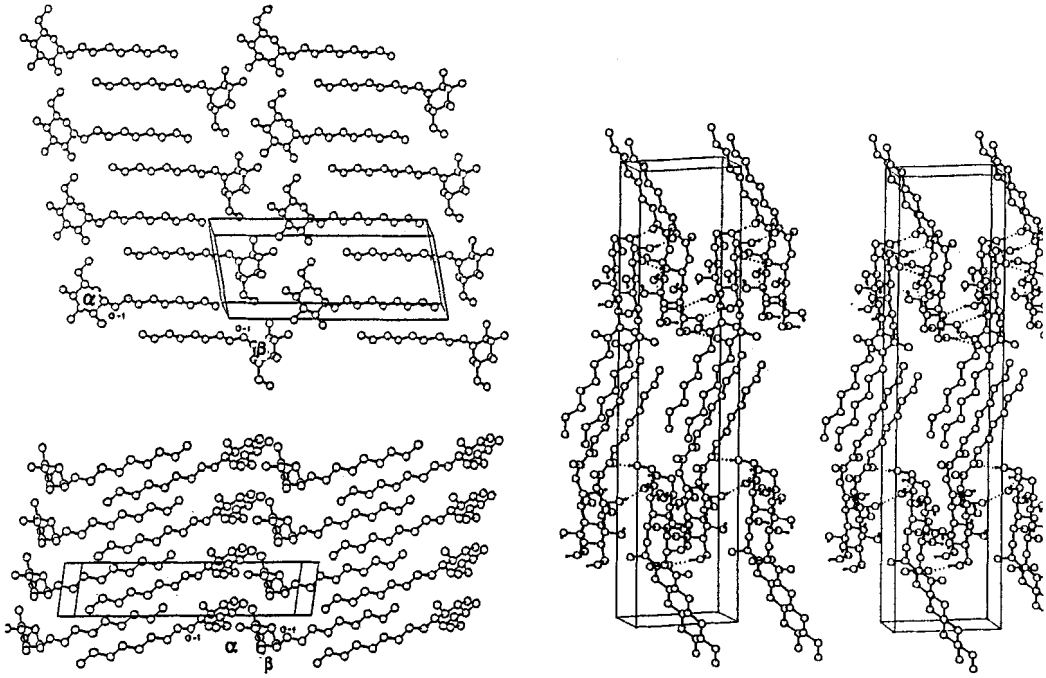
$$HOCH_2{\cdot}(CHOH)_m{\cdot}CH{\cdot}[S{\cdot}(CH_2)_n{\cdot}CH_3]_2 \qquad \textbf{(XVII)}$$

$$HOCH_2{\cdot}(CHOH)_{m-1}{\cdot}CH_2{\cdot}CH[S{\cdot}(CH_2)_n{\cdot}CH_3]_2 \qquad \textbf{(XVIII)}$$

As would be expected, the transition temperatures for derivatives of the pentitols are lower than those for derivatives of the hexitols. Arabinitol itself has a straight-chain conformation in its crystalline state, whereas those of the other three pentitols are bent [87]. This correlates with the higher transition temperatures of the dialkyl derivatives of arabinitol as compared to derivatives of lyxitol, ribitol and xylitol. The xylitol derivatives are liquid crystals at room temperature. In the hexitol series, the dialkyl derivatives of galactitol and mannitol have higher transition temperatures than the

corresponding derivatives of gluctitol. Again, this correlates with the straight-chain conformation of galacitol and mannitol and the bent conformation of glucitol in their crystal structures [87]. It should be noted, however, that the glucitol moiety has a straight-chain conformation in the crystal structure of the 1-deoxy-(*N*-methyl-octamido)-glucitol (MEGA-8) and a bent-chain conformation in the undecamido compound (MEGA-11), see figure 6. In the liquid crystal phase, interchange between these and possibly other energetically favoured conformations is possible.

Removing a hydroxyl group in the 2-deoxy compounds (i.e. one hydroxyl group out of four) results in a liquid crystal at room temperature for the dialkyl derivatives of ribitol, but makes very little difference for glucitol (one hydroxyl group out of five). The presence of a terminal methyl group in the dialkyl derivatives of 6-deoxy-galactose (fucose) and 6-deoxy-mannose (rhamnose) completely inhibits mesophase formation [83, 84, 86]. On the basis of texture and mixing experiments, it was originally thought that the mesophases of these Y-shaped molecules were smectic or smectic-like [82, 83], but X-ray diffraction patterns give three sharp rings more consistent with a hexagonal columnar, H_x, structure with lattice parameters of 28 to 32 Å for the C_8H_{17} derivatives [84]. As with the *scyllo*-inositol *S,S*-dialkyl derivatives, it is suggested that the bulky side chains prevent the formation of smectic bilayers and favour disc-shaped assemblages which form hexagonally packed columns with the alditols in the centre of each column [86] (see figure 2(*c*)). Some crystal structure analyses would be useful to explore the possible modes of packing of these molecules.



(*a*) (*b*)

Figure 4. Head-to-head bilayer packing in the crystal structures of (*a*) Octyl α/β-glucopyranoside (triclinic) [88]. (*b*) 1-Deoxy-*N*-methyl octamido)-glucitol; MEGA-8 (orthorhombic) [94].

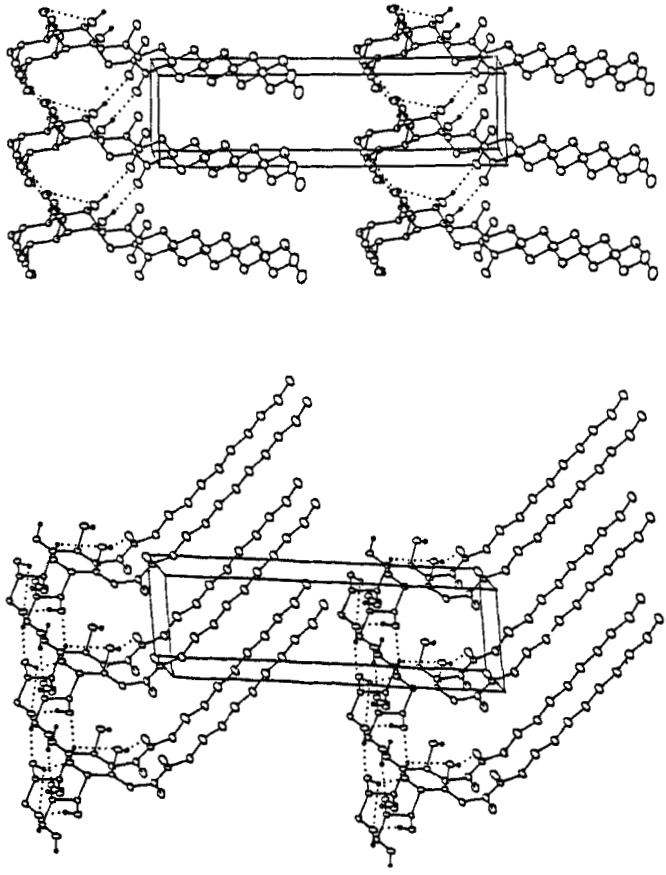


Figure 5. Head-to-tail monolayer packing in the crystal structure of 1-deoxy-(*N*-methyl undecamido)-glucitol (MEGA-11) [94].

3. The crystal structures of carbohydrate mesogens

X-ray crystal structure analyses have been reported for the carbohydrate mesogens shown in table 2. These crystal structure data provide information concerning the energetically more favourable modes of molecular packing at room temperature for crystallizations that are usually from solution. If a series of configurationally related molecules is studied, these structure analyses also give information relating to the conformational flexibility of the molecules. The crystal structures are, therefore, useful as a starting point for hypotheses concerning the changes in molecular packing and in molecular conformation that may take place as the crystal lattices are disrupted by an increase in the thermal motion or the effects of solvation. Bear in mind however that, with the possible exception of the cubic lyotropic phases, most liquid crystals are more like ordered fluids than crystalline solids. No detailed crystal structure analyses have been made of the sequence of crystal structures that often precede the transition to the liquid crystals. Such information might help to resolve the question concerning the choice of models referred to in § 2.1.

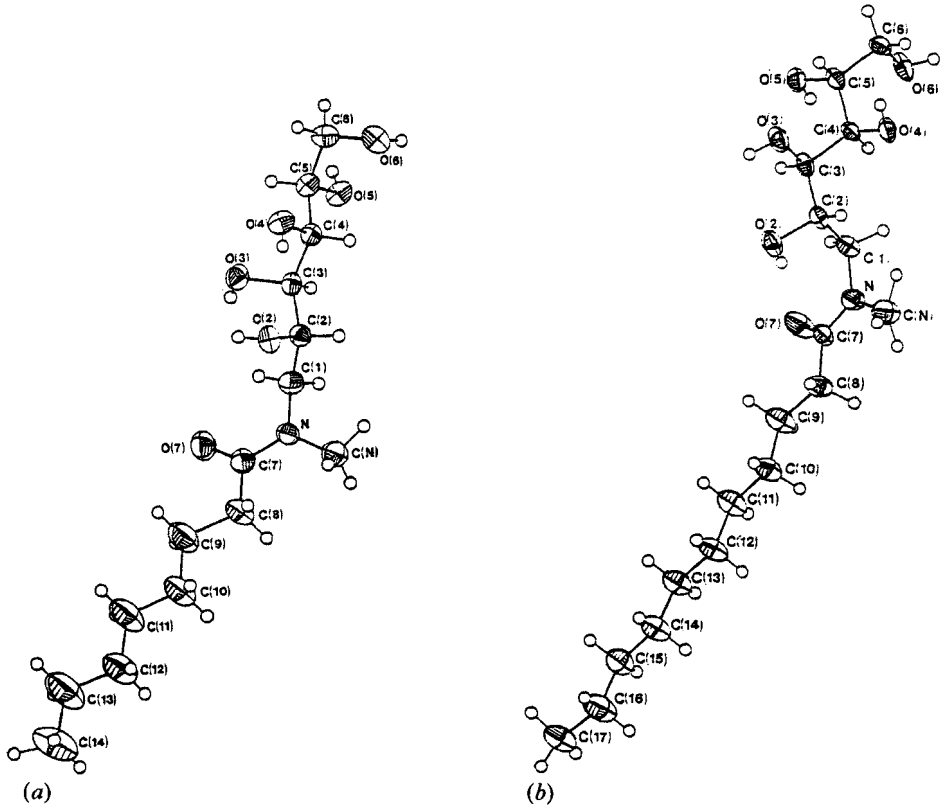


Figure 6. Molecular conformations in the crystal structures of two 1-deoxy-(*N*-methyl alkanamido)-glucitols [94]. (*a*) Straight chain glucitol in MEGA-8. (*b*) Bent chain glucitol in MEGA-11.

Table 2. Crystal structures of carbohydrate mesogens: symmetry: space group and molecular packing.

Bilayer head-to-head structures			Refs
Triclinic	*P*1	1-*O*-*n*-Octyl-α/β-glucopyranoside	[88]
Monoclinic	$P2_1$	1-*O*-*n*-Octyl, *n*-decyl-α-glucopyranoside	[90]
		1-*S*-*n*-Heptyl-α-glucopyranoside	[91]
Orthorhombic	$P2_12_12_1$	1-*S*-*n*-Octyl-β-xylopyranoside	[92]
		1-*S*-*n*-Heptyl-α-mannopyranoside	[93]
		1-Deoxy-(*N*-methyl-octamido)-glucitol (MEGA-8)	[94]
Monoclinic	*C*2	1-*O*-*n*-Octyl-α-glucopyranoside $0{\cdot}5H_2O$	[95]
		1-*O*-*n*-Octyl-α-glucopyranoside H_2O	[95]
Monolayer head-to-tail structures			
Triclinic	*P*1	*N*-(*n*-Decyl)-ribonamide	[96]
		N-(*n*-Heptyl)-gluconamide	[97]
		N-(*n*-Undecyl)-gluconamide	[98]
		1-Deoxy-(*N*-methyl-nonamido)-glucitol (MEGA-9)	[99]
		1-Deoxy-(*N*-methyl-undecamide)-glucitol (MEGA-11)	[94]
Monoclinic	$P2_1$	*N*-(*n*-Octyl)-gluconamide	[100]
		N-(*n*-Decyl)-gluconamide	[97]

All crystal structures of the carbohydrate mesogens hithero studied (see table 2) have one of two types of molecular packing:

(1) head-to-head bilayer structures, with interdigitizing alkyl chains, as shown in figures 4(*a*) and (*b*);
(2) head-to-tail monolayer structures with non-interdigitizing chains, as shown in figure 5.

To date, there have been no examples of carbohydrate amphiphilic structures with bilayers and non-interdigitizing chains, such as observed in the crystal structures of the cerebrosides [101], and are inferred for the structures of membranes. On the other hand, head-to-head bilayer packing with interdigitizing chains in the crystal structure does not imply mesogenic properties. The crystal structures of trihydroxybenzoic acid octyl ester·$2H_2O$ [102] and of 6-*N*-heptylmercaptopurine and 6-*N*-hexylaminopurine [103] have this molecular packing but are not mesogens.

Among crystal structures of carbohydrate mesogens, all three low symmetry, non-centric primitive lattices are represented: triclinic $P1$, monoclinic $P2_1$, $C2$ and orthorhombic $P2_12_12_1$. Characteristically, the unit cells have one long and two short axes. The long axes range from 1·1 to 1·7 times the extended molecular length for both the bilayer and monolayer structures. When an *n*-alkyl series has been studied, as in the gluconamides, structures with odd and even numbered alkyl chains are not isostructural, but have different space groups. In these crystal structures, the sugar molecules are linked by strong cooperative sequential systems of hydrogen bonds, as in the crystal structures of the sugars alone [104]. The X-ray study of the crystal structure and thermotropic transition of *N*-*n*-undecyl gluconamide indicated that the crystal-to-crystal transition which preceded the mesophase transition is from head-to-tail monolayer packing to head-to-head bilayer packing and thence to a bilayer smectic mesophase. On recrystallization, the bilayer crystal structure is formed [98]. It was noted that all seven crystal structures with monolayer head-to-tail packing given in table 2 have a common hydrogen bonding scheme which includes strong cooperative bonding [105]. It is postulated that the increased thermal motion on heating weakens the hydrogen bonds, allowing the molecules to rearrange into the head-to-head bilayer pattern [36].

In general, it is difficult, but not impossible, to obtain these amphiphilic and discotic molecules as single crystals large enough for X-ray structure analysis. The problem of growing adequate single crystals has hitherto prevented crystal structure analysis of the highly soluble alkyl 1-*O*-*β*-glucopyranosides, of the double alkyl chain cyclic and acyclic sugar derivatives, and of the discotic mesogens. When only crystalline powder patterns are available, the strongest, low order powder ring changes to the single intense ring of the liquid crystal phase with a 10 to 20 per cent change in the *d* spacing [74].

In the crystal structures, the *n*-alkyl chains are always straight and fully extended. However, the relatively small barriers to free rotation about polymethylene chains are well-known from the studies of long chain hydrocarbons and long chain fatty acids. There is no reason to believe that the hydrocarbon chains will remain extended in the mesophases (as often depicted). There can also be some variety in the conformation of the carbohydrate component. The hexopyranoses always have the $^4C_1$ chair conformation shown in **I**, so that the hydroxymethyl group *X* is equatorial. In the absence of a bulky group at *X*, as in the pentoses, either $^4C_1$ or $^1C_4$ conformations can occur, and this is a possibility in their liquid crystal phases as well. More flexibility is expected in

the acylic sugar components. In the crystal structures of the alditols alone, the carbon chain of the polyhydroxyl molecules may be straight, i.e. fully exended as in mannitol, or bent as in glucitol, depending upon the configuration of the hydroxyl groups, and the intra- and intermolecular hydrogen bonding [87]. In the liquid crystal phases, both conformations may be possible in static or dynamic disorder.

In the crystal structures of the 1-deoxy-(*N*-methyl-alkamido)-glucitols, both the straight- and bent-chain conformations are observed. Again it is reasonable to assume that there will be similar conformational flexibility of the sugar moiety in the mesophase, particularly if it is at the exterior of the bilayers as in model II, (see figure 2). It is notable that those mesogens formed from the alditols that have straight-chain conformations in the crystalline state, i.e. arabinitol, galactitol and mannitol derivatives, have higher transition temperatures than those that have bent-chain conformations, i.e. ribitol, xylitol and glucitol. This difference in transition temperature is quite significant for the pentitols, but only a few degrees for the hexitols. There is also the potential for conformational flexibility about the bonds which link the alkyl chains to the carbohydrate. In the pyranosides, the exo-anomeric effect is operative, such that the O(ring)–C(1)–O(1)-C(alkyl) or O(ring)–C(1)–S–C(alkyl) torsion angles are *gauche*. In the α-glycosides, the angle is $+$*gauche*, $+60°$ to $+90°$. In the β-glycosides, it is $-$*gauche*, $-60°$ to $-90°$. The energy barrier is probably sufficient to limit the free rotation about the glycosidic C(1)–O(1) in the mesophase. When the link between the sugar and the alkyl chain involves an amido group, as in the aldonamides and alkanamido groups, the partial double-bond character of the peptide C–N bond will tend to lock the molecules into a *cis* or *trans* conformation. All crystal structures observed hitherto have the *trans* conformation. However, variety is observed in the conformation about the N–C(alkyl) bond, which does not have this constraint.

In the crystal structure of *n*-octyl-1-*S*-β-xylopyranoside, the sugar moieties are disordered over two sites, while the alkyl chains are ordered [92]. There are two examples of crystal structures where the sugar moieties are ordered but the alkyl chains are so disordered that the carbon atomic positions cannot be identified. One is *n*-hexyl-*l*-*S*-β-xylopyranoside which does not form a thermotropic liquid crystal phase [106]. The other is *n*-octyl-gulonamide which does form a liquid crystal phase. The solid state ^{13}C CP-MAS NMR spectra for this compound suggest that the disorder of the alkyl chains in the crystal is dynamic rather than static [107]. Dynamic disorder of one or other of the two components of a carbohydrate amphiphilic molecule in the solid state is a concept that requires further investigation.

4. Future directions

The carbohydrates are remarkable as a source of mesogens, since practically every synthesis of a compound with one or two alkyl chains longer than C_8H_{16} attached to an otherwise unsubstituted sugar has resulted in the observation of mesogenic properties. The most straightforward hydroxyl groups to substitute are at the C(1) or C(6) of a pyranose sugar or the termini of an acyclic sugar. Many other alternate sites are possible. If, for example, it becomes possible to substitute selectively an alkyl chain at any one of the hydroxyl groups of the pyranose sugars, then the series of four pentoses and eight hexoses with C_7H_{15} to $C_{18}H_{27}$ would form the basis for 816 mesogens from these monosaccharides alone. A similar variety is possible from the furanose sugars and from the eight pentitols and hexitols.

To be useful in optical devices, mesophase chirality or magnetic polarizability are necessary properties. Although the carbohydrates are chiral molecules, chiral smectic

or nematic phases have not hitherto been found, nor are there any good clues as to how they might be obtained. (A 'chiral bilayer' has been proposed for the micellar fibres in the gels to explain the difference between the stability of these aggregates formed by enantiomorphic and racemic mixtures of the octyl gluconamides [75].) Polarizability has to be introduced through substituents containing aromatic groups. To be useful as surfactants, a high level of solubility in water is necessary. Solubility depends upon the strength of the hydrogen-bonded structure in the crystal versus the stability of the solvated structure. For carbohydrates, solubility is generally unpredictable even between compounds with the same molecular constitution and similar configurations [108]. Up to the present, serendipity appears to be the most important factor in the invention of technologically useful materials in this field. Because some sugars are inexpensive and over-abundant natural products, there is no doubt that the number of mesogens which are synthesized with carbohydrates as the starting materials will continue to increase. These studies will provide more understanding of the phase transitions that occur with amphiphilic and discotic molecules, and offer the jack-pot chance of finding some compounds with useful technological properties.

References

[1] FISCHER, E., and HELPERICH, B., 1911, *Justus Liebigs Annln Chem.*, **383,** 68, reported that *n*-alkyl-1-*O*-glucosides had double melting points.

[2] JEFFREY, G. A., and BHATTACHARJEE, S., 1983, *Carbohydr. Res.*, **115,** 53.

[3] GOODBY, J. W., 1984, *Molec. Crystals liq. Crystals*, **110,** 205.

[4] JEFFREY, G. A., 1984, *Molec. Crystals liq. Crystals*, **110,** 221.

[5] JEFFREY, G. A., 1986, *Accts chem. Res.*, **19,** 168.

[6] BLOCH, H., 1950, *J. exp. Med.*, **91,** 197.

[7] ASSELINEAU, D., and ASSELINEAU, J., 1978, *Prog. chem. Fats Other Lipids*, **16,** 59.

[8] JAHN, R., 1983, *Bacterial Lipopolysaccharides, Amer. chem. Soc. Monograph* (Washington, D.C.), Chap. 8.

[9] FRIBERG, S. (editor), 1976, *Lyotropic Liquid Crystals and the Structure of Biomembranes*, Advances in Chemistry Series 152 (American Chemical Society, Washington, D.C.).

[10] BROWN, G. H., and WOLKEN, J. J., 1979, *Liquid Crystals and Biological Structures* (Academic Press).

[11] STUBBS, G. W., SMITH, H. G. JR., and LITMAN, B. J., 1976, *Biochem. biophys. Acta*, **425,** 46.

[12] MCPHERSON, A., KOSZELAK, S., AXELROD, H., DAY, J., WILLIAMS, R., ROBINSON, L., MCGRATH, M., and CASCIO, D., 1986, *J. biol. Chem.*, **261,** 1969.

[13] BARON, C., and THOMPSON, T. E., 1975, *Biochem. biophys. Acta*, **382,** 276.

[14] CHUNG, Y. J., and JEFFREY, G. A., 1989, *Biochem. biophys. Acta*, **985,** 300.

[15] NOLLER, C. R., and ROCKWELL, W. C., 1938, *J. Am. chem. Soc.*, **60,** 2076.

[16] BARRELL, E., GRANT, B., OXSEN, M., SAMULSKI, E. T., MOEWS, P. C., KNOX, J. R., GASKILL, R. R., and HABERFELD, J. L., 1979, *Org. Coat Plast. Chem.*, **40,** 67.

[17] FENDLER, J. H., 1982, *Membrane Mimetic Chemistry* (John Wiley).

[18] GRAY, G. W., and GOODBY, J. W., 1984, *Smectic Liquid Crystals—Textures and Structures* (Leonard Hill).

[19] CAFFREY, M., 1987, *Biochemistry*, **26,** 6349.

[20] GRUNER, S. M., 1987, *Science, N.Y.*, **238,** 305.

[21] STODDART, J. F., 1971, *Stereochemistry of Carbohydrates*, Chap. 3 (John Wiley), p. 47.

[22] KENNEDY, J. F. (editor), 1988, *Carbohydrate Chemistry*, Chap. 1 (Clarendon Press), p. 3.

[23] (a) TSCHIERSKE, C., BREZESINSKI, G., KUSCHEL, F., and ZASCHKE, H., 1989, *Molec. Crystals liq. Crystals Lett.*, **6,** 139. (b) VAN DOREN, H. A., VAN DER GEEST, R., KELLOGG, R. M., and WYNBERG, H. L., 1990, *Recl. Trav. chim. Pays-Bas. Belg.*, **109,** 197.

[24] BROWN, G. M., DUBREUIL, P., ICHHAPORIA, F. M., and DESNOYERS, J. E., 1970, *Can. J. Chem.*, **48,** 2525.

[25] DE GRIP, W. J., and BOVEE-GEURTS, P. H. M., 1979, *Chem. phys. Lipids*, **23,** 321.

[26] DURETTE, P. L., and SHEN, T. Y., 1980, *Carbohydr. Res.*, **83,** 178.

[27] ROSEVEAR, P., VAN AKEN, T., BAXTER, J., and FERGUSON-MILLER, S., 1980, *Biochemistry*, **19**, 4108.
[28] DELEYN, F., CLAEYSSENS, M., VAN BEEUMAN, J., and DE BRUYNE, C. K., 1978, *Can. J. Biochem.*, **56**, 43.
[29] DORSET, D. L., and ROSENBUSCH, J. P., 1981, *Chem. phys. Lipids*, **29**, 299.
[30] VAN DOREN, H. A., VAN DER GEEST, R., KELLOGG, R. M., and WYNBERG, H., 1989, *Carbohydr. Res.*, **194**, 71.
[31] VILL, V., BÖCKER, T., THIEM, J., and FISCHER, F., 1989, *Liq. Crystals*, **6**, 349.
[32] VAN DOREN, H. A., VAN DER GEEST, R., DE RUIJTER, C. F., KELLOGG, R. M., and WYNBERG, H., 1990, *Liq. Crystals*, **8**, 109.
[33] BAKER, D., WINGERT, L. M., and JEFFREY, G. A., 1991 (unpublished work).
[34] DAHLHOFF, W. V., 1987, *J. Syn. Org. Chem.*, **4**, 366.
[35] KÖLL, P., and OELTING, M., 1986, *Angew. chem. Int. Ed. Engl.*, **25**, 368.
[36] JEFFREY, G. A., 1990, *Molec. Crystals. liq. Crystals*, **185**, 209.
[37] HALL, C., TIDDY, G. J. T., and PFANNEMÜLLER, B., 1991, *Liq. Crystals*, **9**, 527.
[38] LOEWENSTEIN, A., and IGNER, D., 1991, *Liq. Crystals*, **10**, 457.
[39] MARCUS, M. A., and FINN, P. L., 1985, *Molec. Crystals liq. Crystals Lett.*, **2**, 159.
[40] VAN DOREN, H. A., and WINGERT, L. M. (in preparation). (a) SAKURAI, I., SUZUKI, T., and SAKURAI, S., 1989, *Biochem. biophys. Acta*, **985**, 101.
[41] VAN DOREN, H. A., and WINGERT, L. M., 1991, *Liq. Crystals*, **9**, 41.
[42] VAN DOREN, H. A., and WINGERT, L. M., 1991, *Molec. Crystals liq. Crystals*, **198**, 381.
[43] MANNOCK, D. A., LEWIS, R. N. A. H., SEN, A., and MCELHANEY, R. N., 1988, *Biochemistry*, **27**, 6852. MANNOCK, D. A., LEWIS, R. N. A. H., and MCELHANEY, R. N., 1990, *Biochemistry*, **29**, 7790.
[44] JARRELL, H. C., GIZIEWICZ, J. B., and SMITH, C. P., 1986, *Biochemistry*, **25**, 3950.
[45] SEN, A., HUI, S.-W., MANNOCK, D. A., LEWIS, R. N. A. H., and MCELHANEY, R. N., 1990, *Biochemistry*, **29**, 7799.
[46] KUTTENREICH, H., HINZ, H.-J., INCZEDY-MARCSEK, M., KOYNOVA, R., TENCHOV, B., and LAGGNER, P., 1988, *Chem. Phys. Lipids*, **47**, 245. (a) HINZ, H.-J., KUTTENREICH, H., MEYER, R., RENNER, M., FRÜND, R., KOYNOVA, R., BOYANOV, A. I., and TENCHOV, B. G., 1991, *Biochemistry*, **30**, 5125.
[47] PRAEFCKE, K., KOHNE, B., ECKERT, A., and HEMPEL, J., 1990, *Z. Naturf.* (*b*), **45**, 1084.
[48] CHANDRASEKHAR, S., SADASHWA, B. D., and SURESH, K. A., 1977, *Pramina*, **9**, 471.
[49] KOHNE, V. B., and PRAEFCKE, K., 1984, *Angew chem. Int. Ed. Engl.*, **96**, 70.
[50] KOHNE, V. B., and PRAEFCKE, K., 1985, *Chem. Z.*, **109**, 121.
[51] KOHNE, B., PRAEFCKE, K., and BILLARD, I., 1986, *Z. Naturf.* **41** (*b*), 1036.
[52] PRAEFCKE, K., KOHNE, B., STEPHAN, W., and MARQUARDT, P., 1989, *Chemia*, **43**, 380.
[53] KOHNE, B., PRAEFCKE, K., and STEPHAN, W., 1986, *Chemia*, **40**, 14.
[54] KOHNE, B., MARQUARDT, P., PRAEFCKE, K., PSARAS, P., and STEPHAN, W., 1987, *Chemia*, **41**, 63.
[55] KOHNE, B., PRAEFCKE, K., STEPHAN, W., and MARQUARDT, P., 1986, *Chemia*, **40**, 248.
[56] KOHNE, B., MARQUARDT, P., PRAEFCKE, K., PSARAS, P., and STEPHAN, W., 1987, *Z. Naturf.* (*b*), **42**, 628.
[57] KOHNE, B., PRAEFCKE, K., STEPHAN, W., and NÜRNBERG, P., 1985, *Z. Naturf.* (*b*), **40**, 981.
[58] CHANDRASEKHAR, S., and RANGANATH, G. S., 1990, *Rep. Prog. Phys.*, **53**, 57.
[59] NEULING, H. W., STEGEMEYER, H., PRAEFCKE, K., and KOHNE, B., 1987, *Z. Naturf.* (*a*), **42**, 631.
[60] ITOH, T., TAKADA, A., FUKUDA, T., MIYAMOTO, T., YAKOH, Y., and WATANABE, J., 1991, *Liq. Crystals*, **9**, 221.
[61] ZIMMERMANN, R. G., JAMESON, G. B., WEISS, R. G., and DEMEULLY, G., 1985, *Molec. Crystals liq. Crystals Lett.*, **1**, 183.
[62] MORRIS, N. L., ZIMMERMANN, R. G., JAMESON, G. B., DALZIEL, A. W., REUSS, P. M., and WEISS, R. G., 1988, *J. Am. chem. Soc.*, **110**, 2177.
[63] VILL, V., and THIEM, J., 1991, *Liq. Crystals*, **9**, 451.
[64] PRAEFCKE, K., KOHNE, B., MARQUARDT, P., STEPHAN, W., LUZ, Z., POUPKO, R., WACHEL, E., and LEVELUT, A. M. (to be published).
[65] DAHLHOFF, W. V., 1989, *Z. Naturf.* (*b*), **44**, 1105.
[66] DAHLHOFF, W. V., 1990, *Liebigs. Annln Chem.*, 811, 1025.

[67] DAHLHOFF, W. V., 1991, *Liebigs Annln Chem.*, 463.
[68] DAHLHOFF, W. V., 1988, *Z. Naturf.* (*b*), **43,** 1367.
[69] KJAER, A., KJAER, D., and STRYSRUP, T., 1986, *Tetrahedron*, **42,** 1439.
[70] KUMAR, V., and DEV, S., 1987, *Tetrahedron*, **43,** 5.
[71] BAEYENS-VOLENT, D., CUVELIER, P., FORNASIER, R., SZALAI, E., and DAVID, C., 1985, *Molec. Crystals liq. Crystals*, **128,** 277.
[72] PFANNEMÜLLER, B., WELTE, W., CHIN, E., and GOODBY, J. W., 1986, *Liq. Crystals*, **1,** 357.
[73] GOODBY, J. W., MARCUS, M. A., CHIN, E., FINN, P. L., and PFANNEMÜLLER, B., 1988, *Liq. Crystals*, **3,** 1569.
[74] TRISTRAM-NAGLE, S., and WINGERT, L. M., 1990, *Molec. Crystals liq. Crystals*, **188,** 41.
[75] PFANNEMÜLLER, B., and WELTE, W., 1985, *Chem. phys. Lipids*, **37,** 227.
[76] PFANNEMÜLLER, B., and KÜHN, I., 1988, *Macromolek. Chem.*, **189,** 2433.
[77] NAKASHIMA, N., ASAHUMA, S., and KUNITAKE, T., 1985, *J. Am. chem. Soc.*, **107,** 509.
[78] FUHRHOP, J.-H., SCHNIEDER, P., ROSENBERG. J., and BOEKEMA, E., 1987, *J. Am. chem. Soc.*, **109,** 3387.
[79] FUHRHOP, J.-H., SCHNIEDER, P., BOEKEMA, E., and HELFRICH, W., 1988, *J. Am. chem. Soc.*, **110,** 2861.
[80] FUHRHOP, J.-H., and BOETTCHER, C., 1990, *J. Am. chem. Soc.*, **112,** 1768.
[81] FUHRHOP, J.-H., SVENSON, S., BOETTCHER, C., RÖSSLER, E., and VIETH, H.-M., 1990, *J. Am. chem. Soc.*, **112,** 4307.
[82] DAHLHOFF, W. V., 1987, *Z. Naturf.* (*b*), **42,** 661.
[83] VAN DOREN, H. A., BUMA, T. J., KELLOGG, R. M., and WYNBERG, H., 1988, *J. chem. Soc. chem. Commun.*, 460.
[84] ECKERT, A., KOHNE, B., and PRAEFCKE, K., 1988, *Z. Naturf.* (*b*), **43,** 878.
[85] VAN DOREN, H. A., VAN DER GEEST, R., KEUNING, C. A., KELLOGG, R. M., and WYNBERG, H., 1989, *Liq. Crystals*, **5,** 265.
[86] PRAEFCKE, K., LEVELUT, A. M., KOHNE, B., and ECKERT, A., 1989, *Liq. Crystals*, **6,** 263.
[87] JEFFREY, G. A., and KIM, H. S., 1970, *Carbohydr. Res.*, **14,** 207.
[88] JEFFREY, G. A., and YEON, Y., 1991, *Carbohydr. Res.* (in the press).
[89] VAN KONINGSVELD, H., JANSEN, J. C., and STRAAHOF, A. J. J., 1988, *Acta crystallogr.* C, **44,** 1054.
[90] MOEWS, C., and KNOX, J. R., 1976, *J. Am. chem. Soc.*, **98,** 6628.
[91] VAN DOREN, H. A., VAN DER GEEST, R., VAN BOLHUIS, F., KELLOGG, R. C., and WYNBERG, H., 1989, *Carbohydr, Res.*, **194,** 79.
[92] BHATTACHARJEE, S., and JEFFREY, G. A., 1983, *Molec. Crystals liq. Crystals*, **101,** 247.
[93] CARTER, D. C., RUBLE, J. R., and JEFFREY, G. A., 1982, *Carbohydr. Res.*, **102,** 59.
[94] JEFFREY, G. A., and MALUSZYNSKA, H., 1989, *Acta crystallogr.* B, **45,** 447.
[95] JEFFREY, G. A., YEON, Y., and ABOLA, J., 1987, *Carbohydr. Res.*, **169,** 1.
[96] TINANT, B., DECLERCQ, J. P., and VAN MEERSSCHE, M., 1986, *Acta crystallogr.* C, **42,** 579.
[97] MÜLLER-FAHRNOW, A., HILGENFELD, R., HESSE, H., SAENGER, W., and PFANNEMÜLLER, B., 1988, *Carbohydr. Res.*, **176,** 165.
[98] JEFFREY, G. A., and MALUSZYNSKA, M., 1990, *Carbohydr. Res.*, **207,** 211.
[99] MÜLLER-FAHRNOW, A., ZABEL, V., STEIFA, M., and HILGENFELD, R., 1986, *J. chem. Soc. Chem. Commun.*, p. 1573.
[100] ZABEL, V., MÜLLER-FAHRNOW, A., HILGENFELD, R., SAENGER, W., PFANNEMÜLLER, B., ENKELFELD, V., and WELTE, W., 1986, *Chem. phys. Lipids*, **39,** 313.
[101] ABRAHAMMSON, S., KAHLEN, B., and PASCHER, L., 1977, *Acta crystallogr.* B, **33,** 2008.
[102] JEFFREY, G. A., and YEON, Y., 1990, *Acta crystallogr.* B, **46,** 519.
[103] MALUSZYNSKA, H., and JEFFREY, G. A., 1987, *Molec. Crystals liq. Crystals*, **149,** 1.
[104] JEFFREY, G. A., and MITRA, J., 1983, *Acta crystallogr.* B, **39,** 469.
[105] JEFFREY, G. A., and SAENGER, W., 1991, *Hydrogen Bonding in Biological Strtucture*, Chap. 13 (Springer-Verlag), p. 69.
[106] BHATTACHARJEE, S., 1985, Ph.D. Dissertation, University of Pittsburgh, Pittsburgh, Pennsylvania, U.S.A.
[107] JEFFREY, G. A., LUGER, P., ANDRÉ, C., and FUHRHOP, J.-H., 1991, *Program and Abstracts, The 49th Annual Pittsburgh Diffraction Conference*, Columbus, Ohio, U.S.A.
[108] JEFFREY, G. A., and WOOD, R. A., 1982, *Carbohydr. Res.*, **108,** 205.