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Organocatalytic Synthesis of Higher-Carbon Sugars: Efficient Protocol for the Synthesis of Natural Sedoheptulose and D-*Glycero*-L-*galacto*-oct-2-ulose**

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Herein we report a short and efficient protocol for the synthesis of naturally occurring higher-carbon sugars—sedoheptulose (D-*altro*-hept-2-ulose) and D-*glycero*-L-*galacto*-oct-2-ulose—from readily available sugar aldehydes and dihydroxyacetone (DHA). The key step includes a diastereoselective organocatalytic *syn*-selective aldol reaction of DHA with D-erythrose and D-xylose, respectively. The methodology presented can be expanded to the synthesis of various higher sugars by means of *syn*-selective carbon–carbon-bond-forming aldol reactions promoted by primary-based organocatalysts. For example, this methodology provided useful access to D-*glycero*-D-*galacto*-oct-2-ulose and 1-deoxy-D-*glycero*-D-*galacto*-oct-2-ulose from D-arabinose in high yield (85 and 74%, respectively) and high stereoselectivity (99:1).

Introduction

Higher-carbon sugars, with more than six carbon atoms, are widely distributed in nature, where they have important biological functions.[1] For example, well-known members of this family of compounds C_8-KDO (3-deoxy-D-*manno*-oct-2-ulosonic acid) and C_9-Neu5Ac (sialic acid, neuraminic acid) possess interesting biological properties with potential applications as antibiotics.[2] A number of lesser-known heptoses, heptitols, and heptuloses have also been found in living organisms. For example, L-*glycero*-D-*manno*-heptose (L,D-heptose) has been identified as a major constituent of the lipopolysaccharides (LPS) of Gram-negative bacteria.[3] D-*altro*-Heptulose (sedoheptulose, **1**), is a naturally occurring saccharide present as an intermediate in the photosynthetic cycle in its phosphorylated form and also plays a crucial role in the formation of hexoses.[4] Similar eight-chain ketoses occur naturally in a number of higher plants. Well-distributed D-*glycero*-D-*manno*-oct-2-ulose and less abundant D-*glycero*-L-*galacto*-octulose (**2**, Scheme 1) have been found in various plants such as *Persea gratissima* and *Sedum spectabile*.[5]

The synthesis of sugars with carbon chains composed of more than six carbon atoms presents an interesting challenge.[6] Typical synthetic routes for higher-carbon sugars involve homologation of lower-carbon sugars and require the introduction of new stereogenic centers in a controlled manner.[7] Interestingly, organocatalysis, which has emerged as an important methodology for stereoselective carbon–carbon bond formation,[8] has not been commonly applied to the synthesis of carbohydrates.[9] Particularly, *anti*-selective aldol reaction of protected hydroxyacetone (2,2-dimethyl-1,3-dioxan-5-one) with glyceraldehyde resulted in the formation of various isomeric hexoses.[10] Applications of organocatalysis to the synthesis of higher sugars are rare and are limited to the application of dioxanone donor. In 2006, Barbas III and co-workers used diacetono-D-galactose (C-6-aldehyde) as an acceptor in the reaction with 2,2-dimethyl-1,3-dioxan-5-one promoted by (*R*)-proline.[11] More recently, Jarosz and colleagues demonstrated a stereoselective reaction of D-arabinose with the same protected dihydroxyacetone donor, leading stereoselectively to protected oct-2-ulose.[12] The application of 2,2-dimethyl-1,3-dioxan-5-one instead of hydroxyacetone, however, constitutes a significant drawback. In both cases, the reaction proceeds through cyclic (*E*)-enamine, leading exclusively to *anti*-selective aldols.

Previously, we showed that an organocatalytic aldol reaction of unprotected hydroxyacetone with glyceraldehyde may be an alternative tool for the biomimetic synthesis of D- and L-ketohexoses.[13] To realize such goal, we used organocatalysts with proline and serine motifs resulting in either an *anti*- or—more importantly—an elusive *syn*-selective aldol reaction. Herein we demonstrate that the efficient and highly stereoselective preparation of various higher-carbon sugars may also become facile via *syn*-selective organocatalytic aldol reaction

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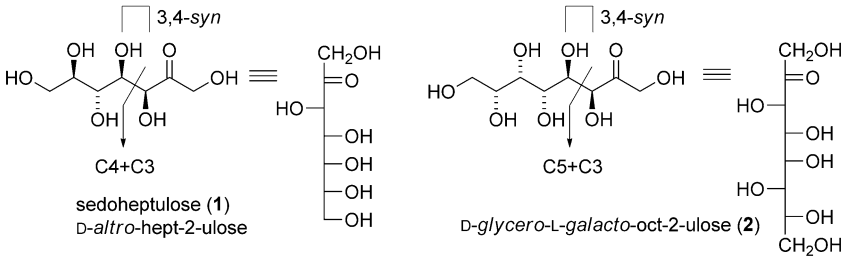


Scheme 1. Natural higher-carbon heptose and octose.

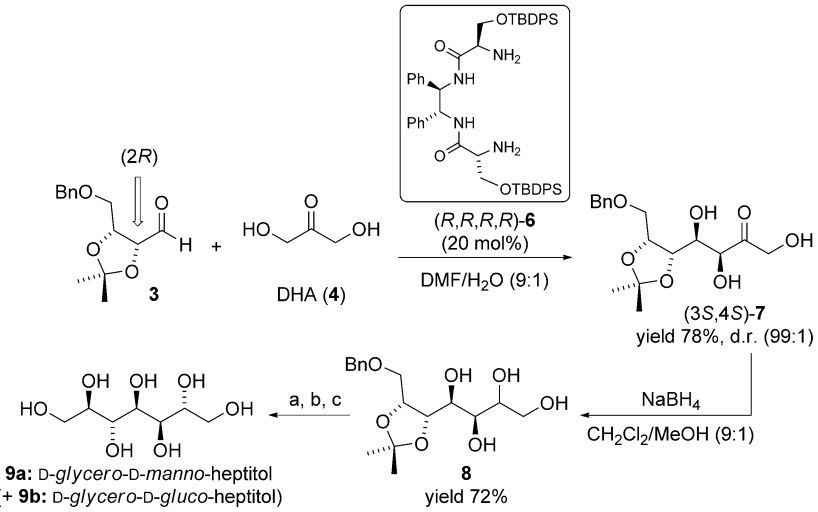
of dihydroxyacetone with the appropriate chiral aldehyde acceptor, complementary to previously demonstrated attempts at *anti*-selective reactions.

Results and Discussion

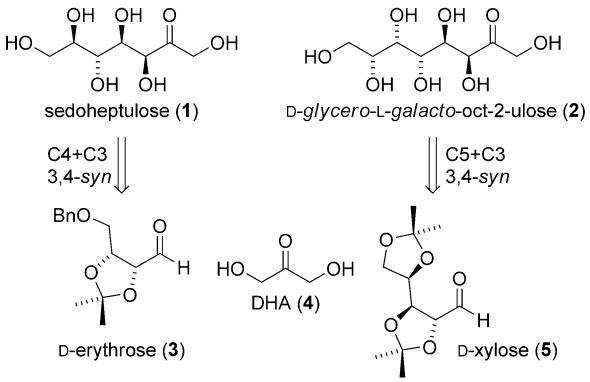
Our retrosynthetic analysis of the sedoheptulose (**1**) and D-*glycero*-L-*galacto*-oct-2-ulose (**2**) skeletons revealed that both structures could be reduced to simple starting materials such as dihydroxyacetone (C_3) and tetrose **3**/pentose **4** through a *syn*-selective aldol reaction. Thinking in the forward direction, such a scenario seemed possible by using a primary-amine-based organocatalyst. It was envisaged that stereochemical control in the synthesis of **1** might be achieved by (*R*)-serine-based organocatalysts with the use of D-erythrose aldehyde **3** as the chiral aldehyde building block (Scheme 2). In this case, the *R*-configured stereocenter at C2 of **3** should match the *R*-configured amino acid resulting in a controlled synthesis of (3*S*,4*S*)-configured stereocenters based on previously deduced principles that (*Z*)-enamine formed from hydroxyacetone attacks aldehyde enantioselectively.[13]

To prove our expectations, we tested the stereoselective aldol reaction of dihydroxyacetone and erythrose promoted by organocatalyst **6** (Scheme 3). The necessary chiral building block, protected D-erythrose **3**, can be synthesized in a few steps from readily available D-mannose.[14] As expected, the crucial aldol reaction promoted by (*R*)-siloxyserine organocatalysts **6** gave hept-2-ulose **7** in 78% yield and high diastereoselectivity, favoring the expected *syn*-aldol (Scheme 3). Application of unmatched catalysts with *S*-configured serine resulted in unselective formation of three isomeric aldols, thus confirming our assumptions.

The absolute stereochemistry of the aldol product is believed to be the same as that of natural sedoheptulose, and this was proven after reduction of the aldol carbonyl group



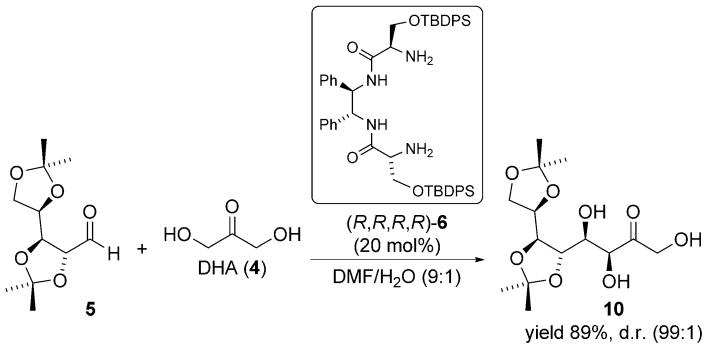
Scheme 3. Stereoselective synthesis of sedoheptulose. *Reagents and conditions*: a) BnBr, NaH, imidazole, Bu_4NI, DMF, 0 °C, 2 h, 79%; b) Amberlyst 15 hydrogen form, MeOH, RT, 24 h, 82%; c) H_2, Pd/C, MeOH, RT, 20 h, 98%. Overall yield: 63%.



Scheme 2. Retrosynthetic analysis of hept-2-ulose and oct-2-ulose.

with sodium borohydride and deprotection of the resulting heptitol **8**. Reduction of aldol **7** afforded two possible C2-epimeric heptitols: D-*glycero*-D-*manno*-heptitol (**9a**) and D-*glycero*-D-*gluco*-heptitol (**9b**) in a 7:3 ratio. ^1H and ^{13}C NMR spectra of both compounds and their peracetylated forms agree with data published previously for the same heptitols,[15] thus ultimately providing evidence for the configuration of sedoheptulose **7**.

Highly stereoselective synthesis of sedoheptulose encouraged us in the synthesis of D-*glycero*-L-*galacto*-oct-2-ulose from protected D-xylose **5**[16] (Scheme 4). In this case, the *R*-configured stereocenter at C2 of the substrate required application of the same catalyst as previously used. Indeed, the reaction of **4** and **5** in the presence of (*R*,*R*,*R*,*R*)-**6** in aqueous



Scheme 4. Stereoselective synthesis of D-*glycero*-L-*galacto*-oct-2-ulose.

DMF afforded **10** as a single diastereomer in high yield (89%). In the case of D-xylose, application of catalyst **6** resulted in the formation of D-*glycero*-L-*galacto*-oct-2-ulose in high yield and diastereomeric ratio. In contrast, enantiomeric catalyst (*S*,*S*,*S*,*S*)-**ent-6** delivered a 1:1 mixture of 3,4-*syn* aldols.

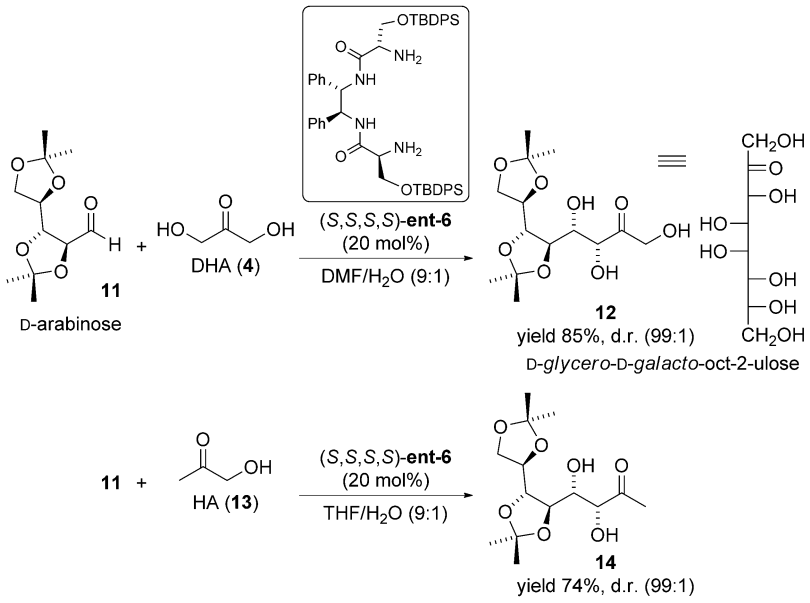
The presented short and stereoselective syntheses of hept- and oct-2-uloses surpass all previously presented routes to such higher-carbon sugars in terms of efficiency; for this reason we decided to test the flexibility of this methodology for substrates with *S* configurations at the α-position to the carbonyl group. In our opinion, the best candidate for such a study was D-arabinose (**11**) with an *S*-configured stereocenter at the α-position to carbonyl group.

The first experiment confirmed our assumptions: the (*S*,*S*,*S*,*S*)-**ent-6**-catalyzed aldol reaction of this substrate with dihydroxyacetone gave the 3,4-*syn* aldol **12** in 85% yield and with high diastereoselectivity (Scheme 5). In this case, the application of catalyst composed of L-serine motifs resulted in the formation of the 3*R*,4*R*-configured aldol. This demonstrated efficient methodology provided synthetically useful access to D-*glycero*-D-*galacto*-oct-2-ulose (**12**). Moreover, application of the same catalyst to the reaction between D-arabinose and hydroxyacetone **13** gave the expected 1-deoxy-D-*glycero*-D-*galacto*-oct-2-ulose (**14**) in high yield (74%) and impressive stereoselectivity (Scheme 5).

In all presented aldol reactions, proper selection of the chiral substrate and aldehyde was decisive, giving us full control over the created stereocenters despite the substrate configuration. When used with chiral *R*- and *S*-configured aldehydes at the α-carbon atom, in the presence of the optional use of (*R*,*R*,*R*,*R*)-**6** and (*S*,*S*,*S*,*S*)-**ent-6** catalysts, a matched/mismatched situation becomes apparent. We confirmed the formation of 4,5-*anti*-3,4-*syn*-aldols exclusively. Application of D-serine-based catalyst (*R*,*R*,*R*,*R*)-**6** was privileged for 2*R*-configured aldehydes and resulted in a predictable formation of 3*S*,4*S*-configured aldols. Such a concept can be useful for the flexible synthesis of various higher sugars by using elaborated catalysts and methodology.

Conclusion

In summary, we report a short and efficient one-step protocol for the synthesis of naturally occurring higher-carbon sedoheptulose (D-*altro*-hept-2-ulose) and D-*glycero*-L-*galacto*-oct-2-ulose, from the readily available sugar aldehydes and dihydroxyacetone (DHA). The key step includes diastereoselective organocatalytic *syn*-aldol reaction of DHA with D-erythrose and D-xylose, respectively. This methodology can be used for the synthesis of various higher sugars by using predictable stereochemistry rules, correlating the absolute configurations of the substrate and catalyst.



Scheme 5. Stereoselective synthesis of D-*glycero*-D-*galacto*-oct-2-ulose and 1-deoxy-D-*glycero*-D-*galacto*-oct-2-ulose.

Experimental Section

General Information: All starting materials and reagents were obtained from commercial sources and used as received unless otherwise noted. All solvents used were freshly distilled prior to use. Optical rotations were measured at room temperature with a polarimeter. High-resolution mass spectra were acquired using electrospray ionization mode with a time-of-flight detector. Infrared (IR) spectra were recorded on a Fourier transform infrared (FT-IR) spectrometer as either a thin film on a NaCl plate (film) or as a KBr pellet (KBr). ^{1}H NMR spectra were recorded on spectrometers operating at 300, 400, 500, and 600 MHz in $CDCl_3$, D_2O, or CD_3OD. Data are reported as follows: chemical shifts (δ) in parts per million from tetramethyl-

silane as an internal standard, integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = double-doublet, m = multiplet, br = broad), coupling constants (in Hz), and assignment. ^{13}C NMR spectra were measured at 75, 100, 125, or 150 MHz with complete proton decoupling. Chemical shifts are reported in ppm from the residual solvent as an internal standard. Reactions were monitored by TLC on silica [alu-plates (0.2 mm)]. Plates were visualized with UV light (λ 254 nm) and by treatment with ethanolic *p*-anisaldehyde with sulfuric and glacial acetic acid followed by heating, aqueous cerium(IV) sulfate solution with molybdic and sulfuric acid followed by heating, or ethanolic ninhydrin solution followed by heating. All organic solutions were dried over anhydrous sodium sulfate. Reaction products were purified by flash chromatography using silica gel 60 (240–400 mesh). HPLC analyses were performed on an HPLC system equipped with chiral stationary phase columns, detection at λ 254 nm.

D-Erythrose (**3**),[14] D-xylose (**5**),[16] and D-arabinose (**11**)[17] acetonides were prepared according to published procedures. Synthesis and spectroscopic data for organocatalysts **6** and **ent-6** were described previously.[18]

General procedure for the aldol reaction of dihydroxyacetone (Schemes 3–5): To a solution of aldehyde (0.5 mmol) in DMF/H_2O (9:1, 0.5 mL), 1,3-dihydroxyacetone dimer **4** (180 mg, 1 mmol; 2 mmol as a monomer) was added. After the substrates dissolved, organocatalyst **6** or **ent-6** (20 mol%) was added to the reaction mixture. The reaction was stirred at room temperature and monitored by TLC. The reaction mixture was poured directly on silica gel. The aldol product was purified by flash column chromatography ($CHCl_3$/MeOH, 97:3).

D-Altro-hept-2-ulose (7, Scheme 3): Yield 132 mg, 78%; $[\alpha]^{22}_D = -12.9$ ($c = 2.38$, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.38–7.27$ (m, 5H), 4.57 (d, $J = 5.3$ Hz, 2H), 4.55–4.50 (m, 1H), 4.48–4.37 (m, 3H), 4.34 (dd, $J = 9.2$, 5.7 Hz, 1H), 4.06 (ddd, $J = 9.2$, 3.5, 1.5 Hz, 1H), 3.93 (d, $J = 3.9$ Hz, 1H), 3.72 (t, $J = 9.5$ Hz, 1H), 3.58 (dd, $J = 9.8$, 3.9 Hz, 1H), 3.19 (d, $J = 8.3$ Hz, 1H), 3.01 (br s, 1H), 1.39 (s, 3H), 1.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 211.7$, 136.4, 128.9, 128.7, 128.3, 109.2, 76.2, 75.8, 75.1, 74.4, 70.0, 68.3, 67.1, 28.0, 25.4; IR (film, $CHCl_3$): 3412, 2986, 2932, 2872, 1726, 1455, 1382, 1375 cm^{-1}; HRMS (ESI) exact mass calcd for $C_{17}H_{24}O_7Na$ *m/z* 363.1420 $[M+Na]^+$, found *m/z* 363.1429 $[M+Na]^+$.

7-*O*-Benzyl-5,6-*O*-isopropylidene-D-glycero-D-mannoheptitol and 7-*O*-benzyl-5,6-*O*-isopropylidene-D-glycero-D-glucoheptitol (8, Scheme 3): After the aldol product **7** was dissolved in CH_2Cl_2/MeOH (9:1) and cooled to 0 °C, $NaBH_4$ (1.2 equiv) was added, and the reaction mixture was stirred for 2 h. Next the mixture was diluted with CH_2Cl_2 and washed with saturated solution of sodium hydrogen carbonate. The aqueous phase was extracted with CH_2Cl_2, and the combined organic layer was dried, concentrated, and purified by flash column chromatography (CH_2Cl_2/MeOH, 93:7). Yield 49 mg, 72%; ^{1}H NMR (400 MHz, CD_3OD): $\delta = 7.41–7.29$ (m, 4H), 7.32–7.23 (m, 1H), 4.59 (s, 2H), 4.44–4.36 (m, 1H), 4.31–4.24 (m, 1H), 3.96 (d, $J = 9.8$ Hz, 1H), 3.89–3.80 (m, 1H), 3.81–3.74 (m, 1H), 3.72–3.64 (m, 2H), 3.64–3.56 (m, 2H), 1.38 (s, 3H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, CD_3OD): $\delta = 139.3$, 139.3, 129.4, 129.0, 129.0, 128.8, 128.8, 109.9, 109.8, 78.0, 77.9, 77.2, 76.9, 75.0, 74.5, 74.5, 72.4, 71.8, 71.2, 71.0, 70.4, 70.3, 68.7, 65.2, 64.0, 28.3, 28.3, 25.9, 25.8; IR (ATR, ZnSe): 3301, 2986, 2941, 2878, 1455, 1434, 1382 cm^{-1}; HRMS (ESI) exact mass calcd for $C_{17}H_{26}O_7Na$ *m/z* 365.1576 $[M+Na]^+$, found *m/z* 365.1582 $[M+Na]^+$.

D-Glycero-D-mannoheptitol (9b, Scheme 3) and D-glycero-D-glucoheptitol (9b, Scheme 3): The reaction was performed under argon. A mixture of protected heptitols **8** (45 mg, 0.13 mmol) was dissolved in anhydrous DMF, and imidazole (10 mol%) was added. The reaction mixture was cooled to 0 °C, and NaH (60% dispersion in mineral oil, 4×1.3 equiv) was added. After 30 min BnBr (4×1.2 equiv) and Bu_4NI (4×0.12 equiv) were added, and the reaction was monitored by TLC. After 2 h H_2O was added to the reaction mixture and the aqueous phase was washed with EtOAc. The organic phase was washed with brine, dried, concentrated, purified by flash column chromatography (hexane/EtOAc 9:1) and submitted to the next step. After the substrate was dissolved in MeOH, Amberlyst 15 hydrogen form was added, and the vial with the mixture was placed on a laboratory shaker. After 24 h the reaction mixture was filtered, concentrated, purified by flash column chromatography (hexane/EtOAc 3:1), and submitted to the next step. Removal of benzyl groups was performed by hydrogenation in the presence of palladium on charcoal. The substrate was dissolved in MeOH, and Pd/C was added. After 20 h of stirring under hydrogen atmosphere the reaction mixture was filtered through a Celite plug and concentrated. Yield 16 mg, 63%; ^{1}H NMR (400 MHz, D_2O): $\delta = 3.91–3.86$ (m, 2H), 3.86–3.83 (m, 1H), 3.83–3.80 (m, 1H), 3.80–3.77 (m, 2H), 3.77–3.75 (m, 2H), 3.75–3.73 (m, 2H), 3.72–3.68 (m, 2H), 3.68–3.65 (m, 1H), 3.65–3.61 (m, 2H), 3.61–3.54 (m, 1H); ^{13}C NMR (100 MHz, D_2O): $\delta = 74.3$, 74.2, 73.9, 73.0, 72.8, 72.1, 71.2, 71.0, 70.9, 64.5, 63.8, 63.5, 63.4; IR (ATR, ZnSe): 3364, 2938, 1648, 1598, 1418, 1311 cm^{-1}; HRMS (ESI) exact mass calcd for $C_7H_{16}O_7Na$ *m/z* 235.0794 $[M+Na]^+$, found *m/z* 235.0796 $[M+Na]^+$.

^{1}H and ^{13}C NMR spectra of the mixture of peracetylated heptitols **9a**/**9b** also match previously published data.[15] The peracetylation reaction was performed under argon. The mixture of heptitols **9a** and **9b** (12 mg, 0.05 mmol) was dissolved in dry pyridine, Ac_2O (30 equiv) and DMAP (10 mol%) were added, and the reaction was kept at room temperature for 24 h. MeOH was added, and the mixture was concentrated under reduced pressure. The residue was partitioned between CH_2Cl_2 and 5% aqueous HCl. The organic layer was washed with 5% aqueous $NaHCO_3$, dried, concentrated, and purified by flash column chromatography (hexane/EtOAc, 3:2). Yield 20 mg, 79%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 5.47–5.40$ (m, 1H), 5.40–5.36 (m, 1H), 5.27–5.18 (m, 1H), 5.16–5.10 (m, 1H), 5.09–5.02 (m, 1H), 4.38–4.28 (m, 1H), 4.25–4.15 (m, 2H), 4.04 (dd, $J = 12.5$, 5.3 Hz, 0.7×1H), 3.96 (dd, $J = 11.7$, 6.3 Hz, 0.3×1H), 2.15 (s, 0.9H), 2.14 (s, 0.9H), 2.13 (s, 2.1H), 2.10 (s, 0.9H), 2.07 (s, 0.9H), 2.06 (s, 2.1H), 2.06 (s, 4H), 2.04 (s, 5H), 2.04 (s, 2.1H), 2.03 (s, 0.9H), 2.02 (s, 0.9H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 170.8$, 170.7, 170.7, 170.4, 170.4, 170.1, 170.1, 170.1, 170.0, 169.9, 169.9, 169.7, 169.7, 169.4, 70.3, 70.1, 69.4, 69.2, 68.8, 68.7, 68.5, 68.2, 67.9, 67.6, 61.9, 61.7, 61.6, 61.5, 21.0, 21.0, 20.9, 20.9, 20.9, 20.8, 20.8, 20.8, 20.8, 20.7, 20.7, 20.6; IR (film, $CHCl_3$): 1749, 1434, 1372, 1217 cm^{-1}; HRMS (ESI) exact mass calcd for $C_{21}H_{30}O_{14}Na$ *m/z* 529.1533 $[M+Na]^+$, found *m/z* 529.1536 $[M+Na]^+$.

5,6:7,8-Di-*O*-isopropylidene-D-glycero-L-galactooct-2-ulose (10, Scheme 4): Yield 142 mg, 89%; $[\alpha]^{21}_D = -9.4$ ($c = 1.85$, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 4.59$ (d, $J = 19.5$ Hz, 1H), 4.54–4.42 (m, 2H), 4.36 (td, $J = 6.9$, 4.2 Hz, 1H), 4.16 (dd, $J = 7.1$, 4.2 Hz, 1H), 4.06 (td, $J = 8.5$, 7.1 Hz, 2H), 3.94 (dd, $J = 8.5$, 7.1 Hz, 2H), 3.48 (d, $J = 6.4$ Hz, 1H), 3.21 (d, $J = 5.9$ Hz, 1H), 3.08 (br s, 1H), 1.45 (s, 3H), 1.43 (s, 3H), 1.41 (s, 3H), 1.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 211.2$, 110.5, 110.2, 79.6, 76.1, 75.7, 74.9, 73.9, 66.8, 65.8, 27.2, 27.2, 26.1, 25.2; IR (film, $CHCl_3$): 3410, 2987, 2935, 1727, 1641, 1456, 1382, 1372 cm^{-1}; HRMS (ESI) exact mass calcd for $C_{14}H_{24}O_8Na$ *m/z* 343.1369 $[M+Na]^+$, found *m/z* 343.1378 $[M+Na]^+$.

5,6:7,8-Di-*O*-isopropylidene-D-glycero-D-galactooct-2-ulose (12, Scheme 5): Yield 136 mg, 85%; $[\alpha]^{24}_D = +5.4$ ($c = 1.01$, $CHCl_3$);

^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 4.63$ (dd, $J = 19.6$, 4.4 Hz, 1H), 4.54–4.42 (m, 2H), 4.26–4.18 (m, 1H), 4.08–4.00 (m, 3H), 3.97 (d, $J =$ 4.4 Hz, 2H), 3.77–3.70 (m, 1H), 3.28 (d, $J = 8.3$ Hz, 1H), 3.01 (t, $J =$ 4.8 Hz, 1H), 1.44 (s, 3H), 1.39 (s, 3H), 1.38 (s, 3H), 1.36 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 211.5$, 110.7, 110.2, 81.3, 79.3, 76.3, 75.9, 73.4, 68.2, 67.1, 26.9, 26.5, 25.1; IR (film, $CHCl_3$): 3424, 2987, 2935, 2898, 1726, 1374 cm^{-1}; HRMS (ESI) exact mass calcd for $C_{14}H_{24}O_8Na$ *m/z* 343.1369 $[M+Na]^+$, found *m/z* 343.1366 $[M+Na]^+$.

5,6:7,8-Di-*O*-isopropylidene-1-deoxy-D-glycero-D-galactooct-2-ulose (14, Scheme 5): A solution of D-arabinose acetonide **11** (115 mg, 0.5 mmol) in THF/H_2O (1:1, 0.2 mL) and hydroxyacetone (HA, 0.9 mL, 13.1 mmol) and catalyst **ent-6** (20 mol%) was stirred at room temperature for 24 h and then directly purified by flash column chromatography on silica gel (toluene/EtOH, 20:1) to afford pure aldol **14**. Yield 113 mg, 74%; $[\alpha]^{22}_D = -44.6$ ($c = 1.00$, $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$): $\delta = 4.37$ (d, $J = 4.5$ Hz, 1H), 4.22 (dd, $J = 8.8$, 6.2 Hz, 1H), 4.10–4.05 (m, 2H), 4.02 (dd, $J = 8.8$, 5.2 Hz, 1H), 3.98 (ddd, $J = 8.7$, 2.7, 1.5 Hz, 1H), 3.80 (dd, $J = 8.7$, 7.3 Hz, 1H), 3.74 (d, $J = 1.9$ Hz, 1H), 3.60 (d, $J = 5.9$ Hz, 1H), 2.31 (s, 3H), 1.44 (s, 3H), 1.42 (s, 3H), 1.41 (s, 3H), 1.35 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$): $\delta = 208.2$, 110.5, 110.1, 81.4, 79.3, 77.4, 76.5, 73.2, 68.1, 27.1, 27.0, 26.4, 25.7, 25.1; IR (neat): 3490, 3456, 2994, 2938, 1706, 1373, 1247, 1219, 1155, 1133, 1078, 1066, 848 cm^{-1}; HRMS (ESI): exact mass calcd for $C_{14}H_{24}O_7Na$ *m/z* 327.1420 $[M+Na]^+$, found *m/z* 327.1422 $[M+Na]^+$.

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